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ORIGINAL PAPER

Reduction and emergence in the physical sciences: Reply to Rueger

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Abstract I analyse Rueger's application of Kim's model of functional reduction to the relation between the thermal conductivities of metal bars at macroscopic and atomic scales. 1) I show that it is a misunderstanding to accuse the functional reduction model of not accounting for the fact that there are causal powers at the micro-level which have no equivalent at the macro-level. The model not only allows but requires that the causal powers by virtue of which a functional predicate is defined, are only a subset of the causal powers of the properties filling the functional specification. 2) The fact that the micro-equation does not converge to the macro-equation in general but only under the constraint of a "solvability condition" does not show that reduction is impossible, as Rueger claims, but only that reduction requires inter-level constraints. 3) Rueger tries to analyse inter-level reduction with the conceptual means of intra-level reduction. This threatens the coherence of his analysis, given that it makes no sense to ascribe macroproperties such as thermal conductivity to entities at the atomic level. Ignoring the distinction between theses two senses of "reduction" is especially confusing because they have opposite directions: in intra-level reduction, the more detailed account reduces to the less detailed one, whereas in inter-level reduction, the less detailed theory is reduced to the more detailed one. 4) Finally I criticize Rueger's way of using Wimsatt's criteria for emergence in terms of non-aggregativity, to construct a concept of synchronic emergence. It is wrong to require, over and above non-aggregativity, irreducibility as a criterion for emergence.

Keywords Aggregativity · Causal power · Emergence · Functional reduction · Inter-level · Intra-level · Multirealization · Reduction · Second-order predicate

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Rueger's paper on "functional reduction and emergence in the physical sciences" aims at showing that Kim's model of "functional reduction" is inadequate to account for some kinds of reduction within physics. True, Kim's interests and motivation lie basically with the reduction of psychological theories. But, following Armstrong and Lewis who have inspired his model, Kim explicitly intends it to cover both the reduction of mental concepts and the reduction of very different types of scientific concepts: according to Kim, physical concepts such as transparency (e.g. of water)[1] and temperature (of a gas), and biological concepts such as the concept of gene[2] are amenable to functional reduction just as well as psychological concepts, such as pain or belief or the particular belief that water is transparent.[3]

Therefore, Rueger's analysis of the reduction of the macroscopic thermal conductivity of a metal bar is not only interesting in its own right, but also relevant as a criticism of Kim's theory, understood as a general theory of reduction applicable to all pairs of theories bearing on the same type of phenomena at different but nearby levels.

Rueger studies a case of reduction between theories bearing on the same type of object, metal bars of infinite length, but describing these objects at different levels—macroscopic and atomic. According to Rueger, the reduction of one theory to the other takes in this case the form of a reduction of the *solutions of the equations* of the macroscopic theory to the solutions of the equations of the microscopic theory. More precisely, it takes the form of an approximation: under certain conditions, the solution of the *micro*scopic equation can be written in the form of a perturbation expansion around some small parameter ε whose leading term is a solution of the *macro*scopic equation, and whose other terms vanish in the limit in which the parameter ε tends towards zero. This represents the vanishing of the microscopic discontinuities. In such a case, in which the solution to the "macro-equation" (i.e. the equation characterising the macro-system) appears as an approximation to the solution of the "micro-equation" (i.e. the equation characterising the micro-system), it seems reasonable to conclude that the continuous macrostructure approximates the discontinuous microstructure.

Rueger interprets Kim as requiring that the outcome of a successful reduction of a higher-level concept or property[4] is *the identification* of the causal powers of the reduced and the reducing property: the lower-level property P is shown to fill the causal role that corresponds to the functionalized higher-level property M; therefore instances of P have exactly the same causal powers as instances of M.

One attractive feature of Rueger's approach to reduction in terms of an approximation relation between solutions to equations of motion is that it provides an interpretation of the "causal powers" of a system or a property of a system: each term of the perturbation expansion of the solution to the system's equation of motion corresponds to one of its causal powers.

Rueger's argument against Kim is this: even in those favourable—or "regular"—conditions in which the solution to the higher-level equation can indeed take the form of a perturbation equation whose leading term is the solution to the microscopic

[1] Cf. Kim (1998, p. 100).

[2] Cf. Kim (1999, p. 10ff).

[3] "I believe most cases of interlevel reduction conform to the model I have just sketched." (Kim, 1998, p. 99)

[4] A little later, I shall come back to the difference between concepts and properties in the context of this debate.

equation, and whose other terms converge toward zero in the limit, those other terms are nevertheless *not strictly equal to zero*.

"Although the behaviour associated with P equals the behaviour of M when the parameter becomes zero, we know that this is an 'idealization'—in reality the parameter does never vanish; the ratio $P/L[=\varepsilon$, the ratio between micro- and macro-scale] in our case is never equal to zero. And therefore, the behaviour generated by P comes close to filling the functional role of M but never actually fills it. In more metaphysical terms: there are always causal contributions from P, which are not needed or which are superfluous for doing the job M was supposed to do." (Rueger, this issue, DOI: 10.1007/s11229-006-9027-y)

Although there is much to be learnt from Rueger's analysis, several points require clarification.

1. A first problem concerns the interpretation of Kim's account. Indeed, it would seem that Causey's (1977) (still very influential and widely accepted) theory of reduction constitutes a more appropriate target for Rueger's objection than Kim's. According to Causey, the reduction of a property P_1 described by theory T_1 to a property P_2 described by a theory T_2 leads to the *identification* of P_1 and P_2.

On Kim's proposal, however, the reduction of M to P does not require, or lead to, the identification of two properties: for this to be possible, M and P would have to be properties both at the same level, i.e. properties belonging to the same type of objects, and of the *same logical order*. However, Kim's theory is intended to be a theory of the relation between *predicates* of *different logical orders*: if M is reduced to P via "functional reduction", M is thereby shown to be *a second-order predicate*, and P is shown to be a first-order predicate designating a property that plays the role described by M. M has no causal powers, because in Kim's theory M is just a functional concept or predicate describing a functional role that P fulfils.

If this is correct, Kim's account does *not* exclude, contrary to what Rueger claims, that P has *other* causal powers beside those mentioned in the description M. Hence, cases in which the perturbation expansion of the solution of the lower-level equation converges towards the solution of the higher-level solution, cannot be used against Kim, insofar as one accepts Kim's general idea that what appear to be higher-*level properties* are really higher-*order descriptions* of properties which are not only lower-level but also first-order.

Rueger's analysis of the heat conduction in the metal bar shows that : "What we are able to establish in 'benign' cases is that the causal powers of (an instantiation of) M [higher-level] are a *subset* of the causal powers of (an instantiation of) P [lower-level]." (this issue, DOI: 10.1007/s11229-006-9027-y). I do not think he is justified in concluding from this that : "According to Kim, this should mean that, for instance, macro conductivity as well as innumerable other physical properties are emergent properties." (this issue, DOI: 10.1007/s11229-006-9027-y). Insofar as functional analysis follows Kim's model, M is a second-order predicate describing a causal role, consisting in a set of causal powers. P can play that role by having those causal powers, and in this sense be a reducing property of M in Kim's sense, and *nevertheless have in addition other causal powers*.

It is especially plausible that Kim's model should not exclude this possibility, given that it is explicitly intended to cover cases of *multiple realization*: if M is (or can be) realized alternatively by P_1, P_2, etc., it can be "locally reduced" to each of P_1, P_2. etc. But such a local reduction of M to P_1 cannot imply that P_1 doesn't have any causal powers different from those described by M: on the contrary, P_1 *must* have such proper causal powers, otherwise M would not be multiply realized after all: P_1's proper powers are what distinguishes P_1 from P_2 and M's other realizers. The powers which make it the case that each P_i locally reduces P are common to all the P_i, but the fact that M is realizable by many different P_is (M's local realizers) implies that each P_i has its own powers that are not shared by the other P_is, and not mentioned in the causal role description contained in the predicate M.

In the terms of Rueger's physical example: the solution to the detailed microscopic equation differs for each individual metal bar, in a set of macroscopically equivalent bars. Each possesses some microphysical "idiosyncratic" properties making it unique at the microlevel. These differences correspond to differences in the higher terms of the perturbation expansion, whereas all macroscopically equivalent bars share the leading term, which is the solution to the macro-equation.

However, I think that Rueger's analysis of this case shows that Kim's thesis that the higher-level predicate does not refer to a "causal kind" or "proper scientific kind" (Kim, 1992, p. 18) or property *cannot be justified on physical grounds*.[5] If we interpret "causal powers" to be what is represented by the different terms of the perturbation expansion, the microsystem has additional powers, but the leading term also describes a causal power, which determines the behaviour of the macrosystem.

2. As Rueger shows, in the case of the thermal conductivity of a metal bar, the solution of the macroscopic equation is *not* an approximation to the solution of the microscopic equation, in the sense that the higher-order terms in the perturbation expansion of the solution of the micro-solution do not converge towards zero if the parameter ε tends toward zero.

Rueger describes the difference between *uniform* (in which the higher-order terms converge to zero, so that the perturbation expansion converges towards the solution of the macro-equation) and *non-uniform* cases (where the perturbation expansion does not converge), by saying: "In the uniform cases we have a *reduction* of M to P while in the non-uniform cases M does not reduce to P" (Rueger, this issue, DOI: 10.1007/s11229-006-9027-y) emphasis Rueger's).[6]

However, his analysis of the mathematical treatment of the non-uniform cases does not establish that reduction is impossible. Rather it shows that reduction, i.e. the representation of the solution to the macroequation as an approximation to the solution of the microequation, can only be achieved by using constraints which are essentially *inter-level*. The lesson of Rueger's analysis of the logical role of the "solvability condition" should be, it seems to me, that we cannot construct the solution of the macroequation on the basis of the knowledge of the solution to the microequation *alone*. Reduction cannot, as is sometimes claimed, be achieved by a priori bottom-up derivation. Even in such an apparently metaphysically innocent case as the thermal conductivity in a metal bar, the solution to the macroscopic equation for heat conservation cannot be derived a priori on the basis of the knowledge of the solution to the microequation (for heat conservation) alone. Some input from above (in other words, from knowledge of the macro-level) is needed to constrain the derivation.

[5] This conclusion gets supplementary support by the analyses Rueger (2000a, b, 2001) and Batterman (2000, 2001) have provided elsewhere, of other physical phenomena.

[6] Batterman interprets the significance of his own analysis of the physical explanation of "emergent" phenomena, which are stable macroscopic features of systems that are independent of microphysical detail in a similar way: "one can have explanation without reduction" (Batterman, 2001, p. 76; cf. also Batterman, 2000, p. 134).

This does not mean, as Rueger claims, that no reduction can be achieved in the non-uniform case. Reduction can be achieved with the help of an "inter-level" device (in the form of the solvability condition), which cannot itself be logically reduced in terms of purely microscopic constraints. This is an important result. It allows to refute such claims as Chalmers and Jackson's (2001) that the information in a complete microphysical description of the world suffices to deduce all macroscopic truths. Rueger shows that this is not even true for macro-*physical* facts.

3. Nickles (1973) has shown that the word "reduction" is used in two very different and incompatible senses, which correspond roughly to philosophical usage of the word and to usage by scientists, in particular physicists. In the philosophers' sense of "reduction", the more fundamental theory reduces the less fundamental; it is in this sense that statistical mechanics reduces (or allows us to reduce) thermodynamics, and that Maxwell's theory of electromagnetic waves reduces classical optics. Nickles calls this form of reduction, establishing a link between theories bearing on the same objects or phenomena but where one describes them at a microscopic and the other at a macroscopic level, "reduction$_1$". Thermodynamics (e.g., the less fundamental) "reduces$_1$", as one can also say, *to* statistical mechanics (the more fundamental).

In the physicist's sense, "reduction" goes in the opposite direction. Here it is the more fundamental (or more precise or more general) theory that is said to reduce to the less fundamental; it is in this sense, which Nickles calls "reduction$_2$", that physicists say that the special theory of relativity "reduces to" classical mechanics in the limit of small velocities (where $v/c \ll 1$), or that relativistic velocity-dependent mass $m(v)$ "reduces to" classical velocity-independent mass m. The philosophers' sense, where the less fundamental "reduces$_1$" to the more fundamental, corresponds to Wimsatt's (1976) "inter-level reduction", whereas the physicists' sense, where the more fundamental "reduces$_2$" to the less fundamental in an appropriate limit of some parameter, corresponds to Wimsatt's (1976) "intra-level" reduction.[7]

Rueger neglects this distinction. However, treating these two clearly very different senses of "reduction" as equivalent leads to confusion: Rueger's strategy consists in analysing cases, which belong according to the criterion of levels (in the micro–macro-hierarchy) to the category of "reduction$_1$", by the conceptual means traditionally used to analyse "reduction$_2$".

The reduction of the macroscopic thermal conductivity $K(x)$ to the microscopic thermal conductivity is a case of reduction$_1$ because it shows how the behaviour of the whole is determined by the behaviour of its parts, just as the interaction between gas molecules in motion determines the overall thermodynamic properties of the gas. In this sense, macro-$K(x)$ should "reduce$_1$" to micro-$K(x)$. However, Rueger treats it with the conceptual means appropriate for reduction$_2$, in order to find out whether, on the contrary, micro-$K(x)$ "reduces$_2$" to macro-$K(x)$ in the limit in which the parameter ε vanishes.

From a purely mathematical point of view, it may appear plausible in this case that it is equivalent to analyse how macro-K reduces$_1$ to micro-K and to analyse how

[7] See Wimsatt, this volume. Maybe it is only in physics that same-level reduction (Nickles' "reduction$_2$") takes the form of an approximation that can be represented as a limit in some appropriate parameter. Indeed, Schaffner (1976) argues that, "in the genetics case [...] the intertheoretic operations which are not limit notions are difficult to specify" (Schaffner, 1976, p. 627/628); therefore, according to Schaffner, Nickles' concept of "reduction$_2$" does not add any clarity to the notion of a "strong analogy" used to characterize two successor theories at the same level in Schaffner's own "general reduction paradigm" (cf. Schaffner, 1967, 1993; Hooker, 1981).

"micro-K reduces$_2$ to macro-K". However, it is unclear whether the latter makes literal sense, given that reduction$_2$ applies to properties situated at the same level in the micro–macro hierarchy. Conceiving micro-K and macro-K as being subject to a reduction$_2$ presupposes that they can be treated as the same kind of property, so that it makes sense to conceive of one as an approximation to the other. Macro-K is a macroscopic property, which has its characteristic conditions of application and measurement, in terms of macroscopic measurable quantities such as temperature gradient and heat flow. But it does not seem to make sense to ascribe this very property at the atomic level. What could the thermal conductivity of individual atoms be? To be sure, something at the microlevel underlies thermal conductivity at the macrolevel, but this micro-grounding properties are of a completely different type: heat conduction in solids is based on electron interactions and vibrations (phonons).[8]

However that may be, Rueger's general strategy to analyse reduction$_1$ (micro–macro reduction), which relates theories describing objects and phenomena at different levels, in terms of reduction$_2$, which relates theories (equations and their solutions) describing objects and phenomena at the same level, is in need of conceptual justification. The difference between the concepts and properties described by theories bearing on different levels may be somewhat hidden, in cases such as the thermal conductivity of a metal bar and the trajectory of damped oscillators in phase space,[9] by the fact that it is possible to write the equations of motion at different levels in a very similar mathematical form. But in many other cases even within physics, it is clear that micro–macro-(different-level) reduction$_1$ cannot be conceived with the conceptual means appropriate for (same-level) reduction$_2$. It would make no sense to ascribe the "order parameter" determining the behaviour of fluids or magnets near critical points to a system described at the micro-level.[10] Nor would it make sense to ascribe biological properties such as heredity, or cognitive properties such as learning to a system as described at the micro-level.

4. In the last part of his paper, Rueger makes an interesting proposal of how to conceive of *synchronic emergence*. In *diachronic* emergence, a qualitatively new feature of a system, for example, a new topological feature of its path in phase space, appears during its evolution. When the damping parameter in the van der Pol oscillator, e.g., goes from a positive value to a negative value, a qualitatively new property (according to topological criteria) of the trajectory in phase space "emerges": the path in phase space changes from circular to spiralling.[11]

Rueger suggests to conceive of synchronic emergence as "the combination of novelty and irreducibility" (this issue, DOI: 10.1007/s11229-006-9027-y). Let us look at novelty first. Rueger construes novelty in terms of Wimsatt's notion of violation of conditions of aggregativity. Wimsatt (1986, 1997) calls a system property aggregative if it is (1) invariant under operations rearranging or interchanging any number of parts of the system, (2) invariant (identical or, if it is a quantitative property, varying only in value) under addition or subtraction of parts, (3) invariant under operation of decomposition and reaggregation of parts, (4) if there are no cooperative or inhibitory interactions among the parts. The same criteria can then be used as criteria

8 See, e.g., Ashcroft and Mermin (1976).

9 See also Rueger (2000a, b).

10 See Batterman (2000, p. 125).

11 See Rueger (2000a, b).

of emergence: the violation of each criterion of aggregativity yields a criterion for emergence.[12]

Rueger justifies the intuition that the van der Pol oscillator's property to have a certain trajectory in phase space is "novel", in the sense Wimsatt gives to "emergent", in other words a non-aggregative property of the whole system, by slightly generalizing Wimsatt's original criteria: the trajectory of the damped van der Pol oscillator comes out as novel because it is not invariant under replacement of those of its parts responsible for damping, by "similar parts" (Rueger, this issue, DOI: 10.1007/s11229-006-9027-y). But one might also consider stronger damping as due to an "addition of parts". Then Wimsatt's criterion (2) justifies considering the topological character of the oscillators trajectory as "emergent". It is not clear though whether the emergent topology of the trajectory is "novel" in a synchronic sense: in the diachronic sense, "novelty" corresponds to the appearance of a new topological feature due to some parameter change. Rueger proposes to interpret synchronic novelty in terms of virtual or "imaginary modifications" (this issue, DOI: 10.1007/s11229-006-9027-y) of the system. If such imaginary modifications lead to a change in the macroscopic topology of the trajectory, this trajectory is emergent. But what does it mean to call it "novel"? To make it explicit, it seems necessary to determine some standard of comparison with respect to which the novelty of the trajectory is to be evaluated. We may try to do this in terms of the distinction between the components of the system responsible for the damping D and the rest, i.e. the unperturbed system U, so that the whole system S is the mereological sum of D and U. The topological trajectory of S can then be judged to be novel with respect to the trajectory of U and also with respect to systems in which D is such that the damping parameter λ has the opposite sign (+ or $-$) with respect to the sign of the parameter λ of S. Then one could say that the part U and the whole D have qualitatively (i.e. topologically) different dynamical properties.

Rueger's example of the topological properties of the trajectory of a system in phase space is certainly an interesting application and illustration of Wimsatt's analysis of emergence as violation of aggregativity.

I question only two points in Rueger's analysis. First, I think it is a remainder of Rueger's earlier (2000a, b) thesis that the concept of emergence is essentially diachronic, and appropriate to characterize the appearance of qualitatively new properties during the evolution of systems, when he says that "the van der Pol oscillator ... has properties which should count as emergent" ..., "*in certain regimes of the damping parameter*" (this issue, DOI: 10.1007/s11229-006-9027-y, my emphasis). If we use the criterion stated above, determining whether the trajectory in phase space is emergent or not by *counterfactual* changes in the micro-base properties, we find that the behaviour of the system is emergent *as such*, not only in those regimes of the parameter where the qualitative change actually appears.

Second, Rueger does not follow Wimsatt in considering violation of aggregativity as sufficient for emergence. Rather, he takes emergence to require both violation of aggregativity—this is what he calls "novelty"—and irreducibility. The van der Pol oscillator is claimed to fulfil this criterion for emergence as well. Rueger argues that the dynamical behaviour of the system is "irreducible" because it does not converge to the behaviour of one part of the system, the undamped oscillator. "We [...] have irreducibility (in my sense) of this novel property to the corresponding property (asymptotic behaviour) of the unperturbed ($\lambda < 0$) system because

12 See Wimsatt (1986, p. 287).

$$\lim_{\lambda \to \infty} x^*(t) \neq \lim_{\lambda \to \infty} x(t), \quad \text{for some } t,$$

where $x^*(t)$ are the solutions for $\lambda > 0$ and $x(t)$ those for $\lambda < 0$." (Rueger, this issue, DOI: 10.1007/s11229-006-9027-y)

But if we consider reduction as resulting from an explanation of properties of the whole in terms of the interaction between the parts in terms of their properties, physics provides us with such explanations, and therefore makes the macroproperties reducible after all.[13] As we have seen above, Rueger's analysis of the solutions to the metal bar equations does not establish the impossibility of reduction. As a criterion for emergence, irreducibility is too strong.[14]

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[13] Batterman (2000) shows that fluids and magnets near their critical points have properties that are emergent in Rueger's sense but can nevertheless be reductively explained.

[14] Thanks to Olivier Massin for his comments on an earlier version of this text.