How the Reductionist Should Respond to the Multiscale Argument, and What This Tells Us About Levels

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Abstract

Recent literature has raised what I'll call the 'multiscale argument' against reduction (see e.g. Batterman (2013), Wilson (2017), Bursten (2018)). These authors observe that numerous successful scientific models appeal to features and properties from a wide range of spatial/temporal scales. This is taken to undermine views that the world is sharply divided into distinct levels, roughly corresponding to different scales, and that each higher level is reducible to the next lowest level.

While the multiscale argument does undermine a naive conception of levels and reduction, in this chapter I argue that alternative views of reduction and levels can withstand this argument. After articulating the multiscale argument in more detail, I show that this does not undermine a version of reduction that accepts methodological pluralism in science, yet maintains that the adequacy of any model can be explained by appeal to details at smaller scales. I go on to discuss a case study – dislocations in steel – used by Batterman and Wilson in defence of the multiscale argument. I argue that the version of reduction advocated above is available in this context. I conclude by arguing that, in light of the multiscale argument, an attenuated conception of levels is required.

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1 Introduction

Models and theories that describe interactions across many different spatial and temporal scales are ubiquitous in science. Such multiscale models are incompatible with a reductionist paradigm that assumes science can be neatly divided into distinct levels, and that sufficiently detailed understanding of dynamical models at lower levels will allow for the prediction of goings-on at all higher levels. This is the core of the multiscale argument against reduction.

In this chapter I respond to that argument by demonstrating that multiscale models undermine one form of reduction but are compatible with an alternate conception of localised reductive explanation, where smaller-scale details account for the explanatory adequacy of the multiscale models.

The multiscale argument and its variants is defended in Batterman (2013, 2020), Batterman and Green (2020), Bursten (2018), Jhun (2019), Massimi (2018), McGivern (2008), Mitchell (2009), and Wilson (2017) among others. Whereas the better known multiple realisability argument against reduction is usually premissed on abstract metaphysical theorising,[1] multiscale arguments appeal to the details of science in practice. This research tradition does an excellent and important job of bringing many aspects of scientific theorising under the lens of philosophy of science. I agree with many of the conclusions of these papers – it's only the implications for the reduction-emergence debate which, in my view, have been overstated.

Before proceeding, it's worth drawing a distinction between two kinds of anti-reductionist argument.[2] Arguments against methodological reductionism establish (in my view, successfully) that many different approaches to scientific reasoning are appropriate, legitimate, and successful, for different scientific projects; as such, methodological reductionists who might claim that top-down approaches are universally worse than bottom-up approaches are shown to be mistaken. However, many of the philosophers discussed below do not simply argue against methodological reductionism, they defend a form of wordly anti-reductionism. This is the view that more fundamental facts and relations are inadequate to explain the entities and regularities described by multiscale models.

[1] See Franklin (2021) for a discussion of how multiple realisation can be reductively explained.

[2] Robertson (n.d.) develops a similar distinction.

I advocate methodological pluralism *and* a kind of non-eliminativist worldly reductionism: to evidence worldly reductionism I appeal to a successful multiscale model, where it's clear that a bottom-up methodology would fail. My evidence, then, for worldly reductionism involves bottom-up explanations that, nonetheless, show why bottom-up modelling methodologies fail. Note that I call this reductionism 'worldly' rather than 'metaphysical' or 'ontological' to emphasise that it is compatible with the existence of non-fundamental entities.

The last bit of ground-clearing concerns claims about levels. Multiscale arguments effectively undermine the stratified hierarchical view of levels (see e.g. Oppenheim and Putnam (1958)), since multiscale models straddle such levels. While reductive explanations might be thought to involve levels, these are not the same as those on which multiscale models reside. This poses a problem for traditional conceptions of levels that results in the following dilemma: either there are a great many more levels than often assumed, or level talk should be abandoned altogether.

To précis the positive argument of the chapter: reductive explanations explain the stability of various features at larger scales, in a piecemeal fashion from the bottom up. As such, they can tell us why it is that the multiscale models are successful, and why it is that methodological reductionism fails. Stability is explained, for each particular stable system or phenomenon, by detailing the structures and processes which legitimate the discarding of many degrees of freedom. That gives rise, in each case, to a descriptively accurate model which is stable with respect to perturbations in the discarded degrees of freedom. Importantly, such reductive explanations are far more localised than the theories that traditionally form the relata of reduction. That's why reductive explanations needn't make the false scaling assumptions that provide succour to anti-reductionists. Reductive explanations can evidence worldly reductionism and methodological non-reductionism: multiscale models describe the stable dependencies between distributed parts of large systems, and those dependency relations and their stability can be explained from the bottom up!

Overall, the multiscale argument deserves more attention than it has received in the philosophical literature. As noted, my goals are not purely critical: I think that such science-in-practice analyses have a great deal to teach us about the nature of the world.

In §2 I develop the multiscale arguments as found in the work of various philosophers. In §3 I develop a defence of worldly reductionism in terms of reductive explanation, and argue that this can avoid the problems with more traditional approaches to reduction. In §4 I cash this out with a case study taken from prominent multiscale arguments due to Batterman and Wilson; I go on to show that this case study is reducible on my account of reduction. In §5 I relate this discussion to accounts of levels in the recent philosophical literature. In §6 I conclude.

2 Multiscale Arguments

Reduction is often taken to imply that any theory which describes phenomena at a particular set of length-scales may be reduced to theories appropriate at smaller length-scales. Multiscale arguments purport to undermine such attempts at reduction. Such arguments work in two distinct ways, both of which will be discussed in this section.

First, reductionism is putatively undermined by ostension: it's demonstrated that some systems are so complicated, and straddle such a wide range of length-scales, that traditional reductionist approaches just have no hope of deriving their behaviour from the bottom up. Second, and more theoretically, multiscale arguments are used to bring out a range of invalid assumptions standardly employed in attempts at reduction. Together these arguments can demonstrate that reduction fails, and explain why it fails. To foreshadow the argument in §3: the explanation of why reduction fails opens the possibility that a more nuanced approach to reduction that does not employ such assumptions may succeed.

I focus on multiscale arguments against reduction due to Julia Bursten, Robert Batterman, and Mark Wilson. Each philosopher is naturalistically motivated and they all appeal to a combination of the two kinds of multiscale argument just mentioned. Since my approach to reduction is not considered elsewhere, the philosophers whose work I discuss may not disagree with my observations.

I'll start by characterising multiscale models, and go on to say what the multiscale arguments are in more detail.

Let's start with a very simple multiscale model. Potochnik (2017, p. 184) describes the relations between oak trees and squirrels. She notes that while oak trees are of the order of 100 times taller than squirrels, the study of population dispersal over time will describe their interactions: "there is evidence that the rate at which oak populations spread is heavily dependent on the dispersal of seeds by squirrels" (Potochnik (2017, p. 184)). Meanwhile, for studies of population dynamics, individual trees interact with a population of squirrels: "[m]asting occurs when trees produce all their seeds in large bursts, which happens only in some years ... [o]ne squirrel does not eat enough seeds to drive trees to evolve masting; it takes an entire population" (ibid.). Thus, Potochnik's example demonstrates that if one is accurately to model the ecology and dynamics of squirrel and oak populations, a wide range of spatial and temporal scales are required.

Potochnik uses this example to make arguments about levels, to which I'll return in §5. However, this example suffices to get an idea of how a multiscale model undermines a simple reductionist view: if one were to attempt to derive the large scale theory of oaks and squirrel populations from the small scale theory of seeds and individual squirrels, one would go wrong because, it's supposed, masting and seed dispersal could not be predicted or explained. This account of reduction is clearly a caricature, and I wouldn't wish to attribute it to Potochnik. However, as we'll see in §3, it's not straightforward to formulate a more sophisticated reductionist framework to deal with such models.

Winsberg (2006, p. 142) defines multiscale as follows: "[t]he fact that three different theories at three different levels of description need to be employed makes the models 'multiscale.' The fact that these different regions interact simultaneously, that they are strongly coupled together, means that the models have to be 'parallel multiscale'." Note that, Winsberg's 'level' should be read as 'scale'.

Winsberg goes on to explain that 'parallel multiscale' indicates that the different scales are interacting so strongly that they have to be modelled in parallel – if one aimed to express the input of one model in terms of a few parameters, and feed it into the other models, then such an approach would fail to be empirically adequate. We need to take into account the variation of details at all the relevant scales in a single model. However, Winsberg does not commit himself to a particular stance in the emergence-reduction debate. As such, while his account has informed the later literature, he does not make claims that I will challenge here.

On the other hand, Batterman (2013) (see also Batterman (2020)) specifically targets reductionism which, he claims, is incompatible with accurate scientific modelling. Batterman stresses that one cannot understand the large scale *straightforwardly* in smaller scale terms – thus he is against a particular form of reduction:

> Of course, the phenomenological parameters, like Young's modulus (related to Navier's ϵ), must encode details about the actual atomistic structure of elastic solids. But it is naive, indeed, to think that one can, in any straightforward way derive or deduce from atomic facts what are the phenomenological parameters required for continuum model of a given material.
> [Batterman (2013, p. 272)]

Batterman draws an unfavourable comparison between a naive scaling strategy – known as 'representative elementary volume' (REV) – and the renormalisation group (RG) strategy. He argues compellingly that, in certain contexts, the RG gets it right where the REV gets it wrong precisely because the RG employs a multiscale modelling strategy.

I don't wish here to discuss the RG in detail: see Franklin (2019, 2020) for discussion of this in condensed matter and quantum field theoretic contexts respectively. Instead I focus on the more general objection to reduction raised in Batterman (2013).

This concerns the idealisations employed when attempting to do without multiscale models; the worry is that such idealisations often lead to inconsistencies between bottom-up and top-down approaches: in order to construct tractable models one generally assumes that a given system is homogeneous at scales smaller and larger than those of interest. Traditional approaches to reduction move from lower-level to higher-level descriptions by simple averaging or other techniques that build on the homogeneous idealisations and ignore the structures relevant at intermediate scales. Batterman argues that, in many cases, the use of such averaging techniques leads to inaccurate predictions which can be corrected only by paying attention to such intermediate scales – multiscale models are exactly those models that pay attention to goings-on at multiple scales.

> I suggest that much philosophical confusion about reduction, emergence, atomism, and antirealism follows from the absolute choice between bottom-up and top-down modeling that

> the tyranny of scales apparently forces upon us. As noted, recent work in homogenization theory is beginning to provide much more subtle descriptive and modeling strategies. This new work calls into question the stark dichotomy drawn by the "do it in a completely bottom-up fashion" folks and those who insist that top-down methods are to be preferred.
>
> [Batterman (2013, p. 257)]

Homogenisation is the process by which we move from accurate atomic models to accurate large-scale continuum models. Batterman notes that this theory "involves appeal to various geometrical properties that appear at *microscales* intermediate between the atomic and the macro" (ibid., p. 258); Batterman refers to such intermediate scales as the 'mesoscale'. Thus, he argues that standard reduction, which solely appeals to bottom-up explanation is inadequate here, and that intermediate multiscale models are required.

Batterman notes that "scientists do not model the macroscale behaviors of materials using bottom-up techniques" (ibid., p. 257). In-principle claims are anathema to Batterman and he concludes from his methodological observations that the multiscale methodology employed by practising scientists provides good reason to dismiss reductionism.

Bursten (2018) makes the anti-reductionist argument more forcefully. She presents a detailed case study about the propagation of nanoscale cracks, and draws a fairly strong set of conclusions. While she admits that her characterisation of reduction is somewhat crude, she supposes that the reductionist would favour the smallest scale quantum-mechanical model to the exclusion of the others. She then notes that this model:

> does not have the conceptual resources to account for many of the features of interest of the simulated system. There are phenomena captured in the snapshot that quantum mechanics cannot resolve with its lens. Pressure waves, elastic strain, and thermal fluctuations in a solid are macroscopic, or occasionally mesoscopic, phenomena. Thermal fluctuations in particular simply cannot be tracked by quantum-mechanical descriptions of a system, and to deny their genuine reality, as this reductionist lens would, is to willfully ignore how materials really behave

[Bursten (2018, p. 162)]

As noted above, I agree with methodological anti-reductionism – that accurate modelling of systems also requires consideration of multiple different non-fundamental spatiotemporal scales. But a subtler form of reductionism, which asserts that the adequacy of the non-fundamental models can be explained from the bottom up, is not thus refuted. In fact, while Bursten repudiates reductionism of any variety, she goes on to argue (p. 164) that "[i]t is both possible and, for the purposes of multi-scale modeling, necessary, to develop accounts of how different theories at different scales can be constructively combined to model material behavior." As such, the more piecemeal approach to reduction advocated below may be countenanced.

I agree that understanding multiscale reasoning is an important task for philosophy of science. I argue, however, that such reasoning can be explained and understood in a way that justifies a particular reductionist attitude. Namely, that the working parts of such models are empirically adequate because of legitimate abstractions away from more fundamental goings-on; and that the legitimacy of such abstractions can be reductively explained. In particular, I claim that it is the details of the smaller-scale models which explain why, for example, a description in terms of pressure waves is successful, even if such a description is not available in terms of the entities at small scales.

Bursten and Batterman's detailed arguments demonstrate, primarily by example, that straightforwardly or naively scaling up from a given microscale description will fail to take into account the complex mesoscale structure. Thus, multiscale models which take into account such structure are necessary to good science.

Mark Wilson's work likewise engages with multiscale models, and at length draws out the complexity of such models and their incompatibility with standard reductionist approaches. However, what's especially relevant here is that Wilson does more than either Bursten or Batterman to provide a theoretical account of why reduction fails. His work can therefore be used to draw out and clarify the putative incompatibility between reductionism and multiscale models.

Wilson explicitly has Nagelian reduction in view. The state of the art Nagelian approaches take all the scientific dependencies at some higher

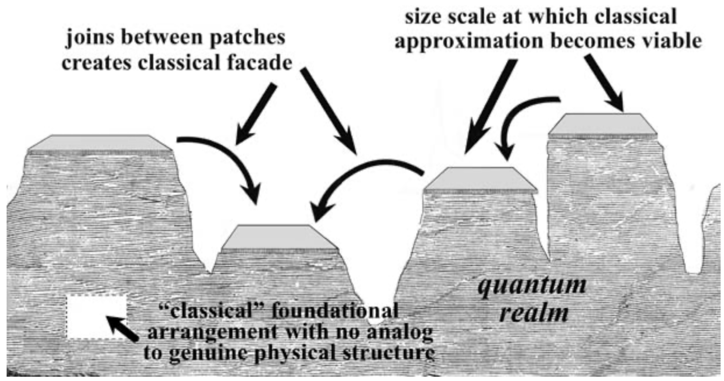

Figure 1: A theory façade, from Wilson (2006, p. 196).

level, re-express them in the terminology of the lower level, and derive them from the lower-level theory, while allowing that the derivation may only recover an approximation; see e.g. Butterfield (2011), Dizadji-Bahmani, Frigg, and Hartmann (2010), and Schaffner (2013).

Wilson observes that when reductionists attempt their bottom-up derivation they fail to take account of certain ways in which theories work. For Wilson, a theory is a theory façade, which is, in his inimitable prose, "an uneven pile of pasteboard cutouts that ably masquerade, from selected angles, for an integral metropolis" (Wilson (2006, p. 356)); see figure 1.

Theories involve a series of loosely and complexly connected methods and problems which suit different domains. For example, classical mechanics, which is further discussed in Wilson (2013), treats rigid bodies, point masses and continua as its fundamental objects in different contexts. The concept of the theory façade is not just applicable to classical mechanics, it is widespread in science. If we accept, following Wilson, that 'scientific theory' corresponds to a much more diverse, loosely bound notion than one might otherwise have assumed, the idea that one can reduce a theory is mistaken. At best one can reduce the localised application of different theories in particular contexts.

As such, care is required when importing the putative referents of theoretical terms from one context to another. For example, when creating a model of a particular system in a context, certain assumptions may apply: it may be permissible to model the system as if everything outside the region in question is uniform and that the environment can be captured by specific values for simple parameters. However, as Wilson emphasises, such simple parameters and assumptions often mask a huge amount of intricate detail. When re-describing the same system in a different context such assumptions will, in general, no longer apply, and the complexity of the environment may preclude description by simplified models.

For our present concerns: when attempting to model a given system from the bottom up, it is common to assume certain kinds of homogeneity. Insofar as such assumptions are mistaken, bottom-up modelling goes wrong. Thus, by focussing on exactly how such assumptions can go wrong, Wilson urges a much more nuanced account of inter-scale relations in science.

As is shown in the case study in §4 – discussed in Wilson (2017, chapter 5), Batterman (2013), and Batterman and Green (2020) – assumptions that are justified in certain contexts idealise away intermediate scales and thus lead to false predictions in other contexts. Wilson aims to impress upon philosophers that modelling in science is a finicky process and that one should pay attention to the kinds of idealisation smuggled into each particular case. It's only very special systems that are well-modelled as ideal gases or perfect crystal lattices for which we may accurately assume an homogeneous environment.

The arguments of Batterman, Wilson, and Bursten all raise doubts that attempts at reduction can adequately comprehend the nuance and complexity of real science. The correct reductionist response to these worries is to advocate a subtler approach to reduction: one that takes into account the intricacies of the mesoscale and is premissed on localised reductive explanation.

3 Reductive Explanation

An important upshot of these criticisms of reduction is that science doesn't work in neatly stratified levels, and that expectations of the behaviour of some parameter in some context will not in general carry over to other contexts. These, together, cast a shadow over the prospects for any grand reductionist project.

In this section I set out and develop an approach to reduction that is piecemeal, and very careful not to import warranted assumptions from one domain into another. The downside of piecemeal approaches to reduction is that one can no longer hope to complete the reductionist project and establish once and for all that reductionism is true or false.

What we can do instead is satisfy the more modest goal of increasing or decreasing credence in worldly reductionism by addressing those specific contexts in which anti-reductionist arguments have been put forward. That is, where some have claimed that the properties of such and such are inexplicable from the bottom up, the more modest reductionist may step in with a bottom-up explanation for why such and such has those properties. The provision of bottom-up explanations is no trivial endeavour, and it's explicitly claimed by Bursten and Batterman that bottom-up explanations will often fail. As such, this is a meaningful form of reduction, and it's an important scientific and philosophical question whether or not it will succeed. Insofar as it does succeed, we will have established that a form of worldly reductionism is compatible with the multiscale complexity of the world.

In contrast to the Nagelian, I focus on reductive explanation rather than derivation. This is for two reasons: first, in some contexts reductive explanation may increase one's credence in reductionism even while the science is insufficiently mathematised for derivation to go through; second, derivation sometimes requires the kind of unphysical assumptions that the multiscale argument forces us to shun. However, explanation should be understood as ontic rather than epistemic: one may understand the explanations discussed here as appealing to a chain of worldly dependencies that relate the *explanans* to the *explanandum*; see e.g. Woodward (2003).

With all that said, I'll explore this concept of reductive explanation in more detail, and show how this can account for the effectiveness of multiscale models in fairly abstract terms. In §4 I'll apply this reasoning to a multiscale model case study.

The central function of the reductive explanations considered here is to explain why the variables used to model dynamics in a given physical system are well suited to this job. Where a system is well described by a multiscale model a number of variables, corresponding to different scales, will account for a system's interactions and dynamical evolution. Why these particular variables are the right ones to describe this system should be reductively explicable if some form of worldly reductionism can be evidenced. If it's not possible to explain why these variables work to describe this system – that is, if the success of a given multiscale model cannot be accounted for from the bottom up – then we have evidence against worldly reductionism. Any conclusions from such evidence will depend on the maturity and consequent warrant for realism of the relevant models and theories.

The way to explain why it is that certain variables are well suited for explanatory and predictive purposes is to identify processes and structures which pick out classes of variables as robust with respect to changes in underlying variables.

Take some set of variables $\{\mu_s, m_t, M_u\}$, found at micro, meso, and macroscales respectively, that are used together in a multiscale model; the applicability of each variable will depend on its robustness with respect to various relevant perturbations; reductive explanation is achieved if it can be demonstrated, from the bottom up, which processes and structures are responsible for the robustness of each variable. This might involve, for example, the demonstration that M_u is robust with respect to perturbations in some subset of $\{\mu_{i\neq s}, m_{i\neq t}\}$, and that m_t is robust with respect to perturbations in some subset of $\{\mu_{i\neq s}\}$.

Multiscale models work by describing dynamics among a set of variables which is strictly smaller than the set of all variables that describe the system at all scales. Reductive explanation then tells us why it works to use the multiscale model rather than just having to describe the system in its entirety while keeping track of the interactions of every atom and every electron etc.

Note that, when referring to variables, I intend this plurally: variables feature in mathematised sciences, as well as in less formal scientific descriptions. Variables refer to worldly degrees of freedom, and, as such, the demonstration that a variable is stable with respect to perturbations is reason to believe that the associated degree of freedom has corresponding stability.

Note in addition that reductive explanations do not take any specific phenomena as their *explananda*. Rather reductive explanations explain the salience and goodness of the variables used to describe such phenomena. Therefore, if one has the relevant reductive explanations to hand, then this does not signal eliminativism. That's because reductive explanations do not explain the phenomena of the multiscale model; rather, they explain the effectiveness of that model for its target phenomena.

To recap: the multiscale argument raises problems with Nagelian reduction. It shows that by treating a theory rather than localised applications of that theory, one idealises away crucial mesoscopic facts, and that interaction between different scales means that scale to scale reduction is impossible.

Reductive explanation has the potential to remedy these issues. The approach is far more localised than Nagelian approaches, thus explaining the salience and effectiveness of particular variables for models in specific contexts; in addition, it's explicitly targeted at explaining why multiscale models work – as such, it takes seriously multiscale interactions. The best way further to evidence these claims is by example, which I offer below.

Predictively accurate science can proceed in ignorance of the details of the composing materials or the goings-on at shorter temporal and spatial scales – many such details are irrelevant to multiscale model prediction and explanation. The reductive question is: can we explain such irrelevance of detail from the bottom up? Reduction is thus hostage to empirical fortune; reduction succeeds only in those circumstances where such explanations go through.

One advantage of the piecemeal approach to reduction advocated here is that it is clearly ontologically non-eliminativist, that's in part because the larger scale and multiscale models group and organise the world in a different way than their multiple reductive bases.[3] Unlike with grander wholesale approaches to reduction, there is no single base theory that might purport to supplant the reduced theory.

4 Dislocations and Train Tracks

The aim of this section is to present a multiscale model to which Nagelian reductions are ill suited but where reductive explanation sheds light. The case study of dislocations is especially apt for assessing the consequences of the multiscale argument against reduction – in a clear physics-based example it seems to show the use of top-down reasoning which cuts against reductionist bottom-up intuitions. Thus it's worth investigating in detail.

The discussion in this section is largely drawn from Wilson (2017, chap-

[3]This idea is very closely related to the cross-classification discussed in Franklin and Robertson (2021).

ter 5), with the more detailed physics and maths drawn from Fan (2011), Friedel (1979), and Lu (2005). Figures 2 and 3 ought to be helpful in understanding the example.

Figure 2 depicts steel at various different length-scales. The scientific descriptions at these different length-scales interact in non-trivial ways. By paying attention to a variety of treatments at intersecting scales one can paint a picture that explains the relevant properties of steel bars or train tracks.

Wilson observes that, before the structure of dislocations was understood, the resistance of steel to breaking was mysterious. If one were to model steel simply, with a uniform lattice structure throughout, then one would predict that strains above a certain threshold would lead to large-scale steel deformation. That is, one would expect steel to be far more brittle than it in fact is. Wilson appeals to this case study in order to demonstrate the extent to which the assumptions of mesoscopic homogeneity may go wrong. It was only with the discovery of the mesoscale structure – the dislocations – that it was understood why steel is not brittle. Thus, only where the homogeneity assumptions are violated and the mesoscale structure is taken into account are accurate predictions for steel deformation available.

Dislocations are a general term for various ways in which an otherwise regular lattice is locally irregular; see figure 3 for some examples of dislocations in two dimensional crystal lattices. The general idea is that steel train tracks can be manufactured with multiple dislocations throughout and that dislocations can move through the material. When the material is struck, or a force is otherwise imposed, the energy is dissipated via the motion of dislocations. While one might expect materials to change shape if struck, the ability approximately to retain shape depends on such motion.

> [The dislocations'] easy-to-achieve movements shield the underlying molecular bonds from the shearing distortions they would otherwise experience if the full impetus of the original blow had been allowed to reach their bonding sites directly. The net result is that RVE [representative volume element] units containing a plentitude of dislocations generally retain their dominant upper-scale behaviors far longer than they could if the dislocations weren't there, due to the fact that the dislocations significantly lessen the danger of fracture at the molecular lattice level.

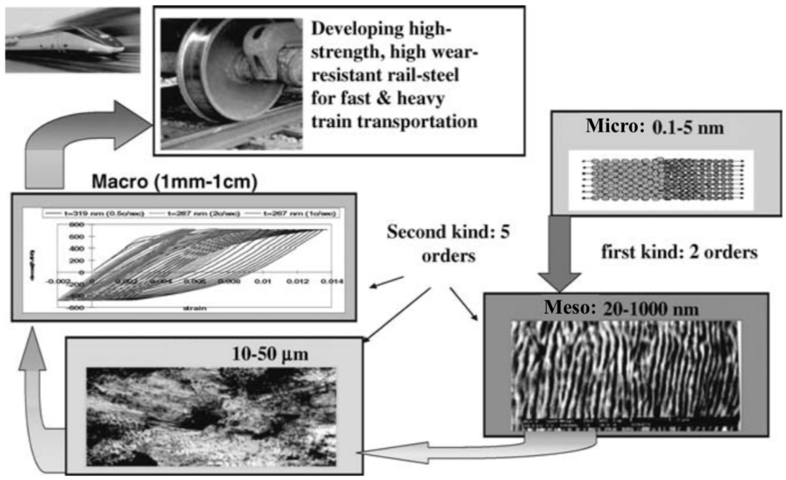

Figure 2: The multiple scales at which high-strength, high-resistance rail steel must be modelled. From Fan (2011, p.10) and Fan, Gao, and Zeng (2004).

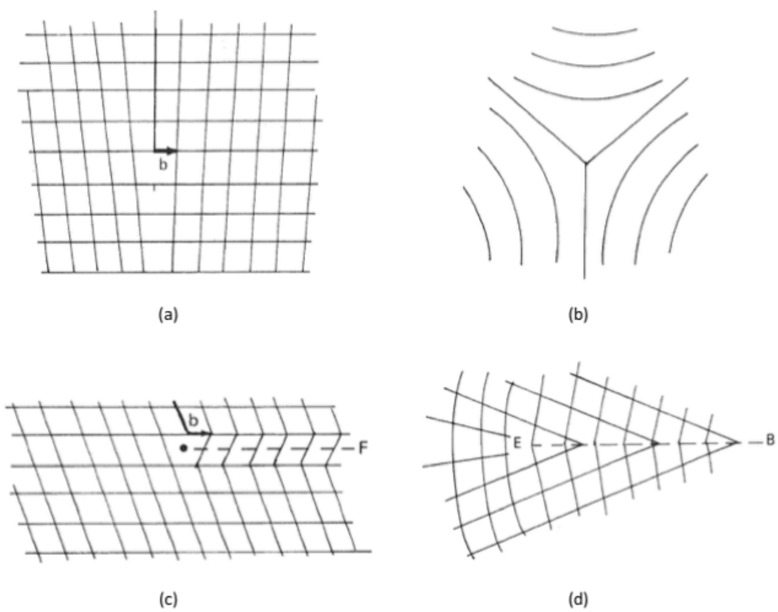

Figure 3: Dislocations in crystals: (a) translation dislocation, (b) rotation dislocation; imperfect dislocations in a crystal: (c) translation dislocation with stacking fault F, (d) rotation dislocation with grain boundary B. From Friedel (1979, p.11).

[Wilson (2017, p. 212)]

Steel may have additional structures known as 'cementite' – 10-50μm in figure 2 – through which dislocations cannot move; this explains why in certain circumstances steel may be brittle. The applicability of models used to describe the steel system is, thus, sensitive to the particular position of the dislocations. As long as most dislocations are relatively far from the cementite barrier, we may understand the dislocations as free, and therefore characterise the steel rail as sufficiently ductile to accept significant stresses. However, if the dislocations face a cementite barrier, a wholly different model with different kinds of assumptions is required to characterise the system's properties and responses to stress.

> [W]e cannot develop an adequate account of [steel] rail hysteresis working upwards from the molecular scale in a naïve manner. Multiscalar models evade these computational barriers by enforcing a cooperative division of descriptive labor amongst a hierarchy of RVE-centered sub-models, each of which is asked to only worry about the dominant behaviors arising within its purview.
>
> [Wilson (2017, p. 221)]

To summarise the case just considered: the scientific problem was that assuming mesoscopic homogeneity of steel led to inaccurate predictions for the hardness of steel; the resolution was to take into account mesoscopic structure – dislocations – which are responsible for absorbing energy from applied stress; this led to more accurate predictions of the fracture threshold of steel. The explanation of such improved predictions requires taking into account structure which is putatively left out in certain attempts at Nagelian reduction. Overall, the idealising assumption that microscopic symmetry carries on all the way up was shown to be mistaken.

This example clearly involves multiscale dependencies: the macroscale properties of the steel depend on the conditions at mesoscales and microscales. In order accurately to determine the fragility of a given piece of steel, one needs knowledge about its dislocation structure and the location of cementite barriers.

The challenge to traditional approaches to reduction arises from the tendency among its practitioners to make a large variety of homogeneity assumptions, which license scaling up the microscale description. In this context, such assumptions lead to inaccurate predictions.

4.1 Case Study Reduced

The case study shows that it's a mistake to assume that one can simply ask 'what will happen when this lattice undergoes this stress?' by scaling stress down and considering the effect on a small, regular segment of the lattice. To do so would hugely overstate the brittleness of the material. In other words, one needs to correct the scaled-down parameters by taking into account the intermediate structure of dislocations. One can't straightforwardly smear out the mesoscopic structure. Motivated by such considerations, from this and other case studies, Bursten and Batterman argue that reduction fails; this is based on the assumption that reduction requires a conception of the structure of materials which fails to take into account the true complexity of multiscale dependencies. In this section, I challenge that assumption.

It's important to note that Wilson is not anti-reductionist in the same sense as the other philosophers whose views I considered above. While he is similarly critical of those who discuss idealised theories – he claims they suffer from 'theory T syndrome' – he is quite sympathetic to approaches which seek to evidence reduction by articulating the intricate interdependencies of various scientific models. In many respects, my approach advocated here is consistent with Wilson's observations.

In order adequately to describe material structure, it is often necessary to take account of communicating interconnected submodels: this will involve, for example, characterising the mesoscopic structure in terms of interlocking parts of cementite and dislocations. The question of interest in this section is whether one may explain, from the bottom up, the explanatory and predictive success of each interlocking mesoscopic model and of the cooperation of these models.

My claim is that one can show from the bottom up how the salient variables are robust and what leads to their playing roles in successful models. Although reductive explanation does not undermine many of the philosophical observations raised in §2, it blocks the general objections to worldly reductionism. Since I do not seek to defend eliminativist reduction, I don't need to show how we can describe each system entirely in terms of its smallest scale components; I rather aim to establish that each multiscale model variable is robust as a consequence of small scale dependencies, and that there is no in-principle barrier to bottom-up derivation as long as that's sufficiently piecemeal.

So let's return to dislocations and consider how their description relates to that of the underlying lattice. I'll go on to ask whether or not reductive explanation goes through in this context.

Dislocations correspond to various types of localised disturbances to the lattice symmetry. They can be mobile and move through the lattice. They are often holes or gaps in the underlying lattice configuration. The relation between the dislocation variables and the underlying atomic lattice is illustrated in figure 3.

While the full story is far more complex than I can discuss here, the central features on which I focus are that the dislocations are irregularities within the lattice and that they may travel through the material. These may be further understood by appealing to the Peierls-Nabarro (P-N) model; see Lu (2005) for an overview. This model allows for quantitative analysis of the size of dislocations and the force required for their motion. The model is a quasi-continuum model in that it selectively treats the lattice as composed of discrete atomic sites, and as a continuum. The continuum treatment, where used, allows for a considerably simpler model, although in certain places this leads to quantitative errors some of which are corrected in the Semi-Discrete P-N model. There are many ways to model dislocations; my goal here is to show one way that this is done and to discuss the extent to which this can be used to evidence a certain form of worldly reductionism.

In equilibrium, according to the P-N model, the distribution of atoms that constitutes a dislocation is determined by two distinct, competing contributions.[4] It costs energy to move atoms out of their positions in the equilibrium regular lattice. One part of this energy cost is the generalised stacking fault (GSF) energy: this is the sum of the misfit energy cost due to dislocated atoms and corresponds to a restorative force which attempts to make the dislocation smaller.

The elastic force opposes the restorative force and corresponds to the elastic energy. If one imagines the lattice split into two elastic half-spaces

[4]Dislocations may move in two ways: either by gliding or by climbing. I will only consider dislocation motion in the glide plane. In addition, I only discuss translation dislocations.

on either side of the dislocation, the movement out of regular equilibrium of all atoms on either side of the dislocation incurs an energy cost. Thus the elastic force attempts to make the lattices regular on either side of the dislocation, and as such to increase the size of the dislocation.

The model describes these forces mathematically, minimises the total energy and thus predicts an equilibrium structure of the dislocation, in particular the half-width of the dislocation core. Equation (1) describes the total dislocation energy on this model for dislocation density $\rho(x)$, generalised stacking fault energy $\gamma(\delta(x))$, elastic factor K, and long distance cut-off L.

$$U_{tot}[\rho(x)] = \overbrace{\int_{-\infty}^{+\infty} \gamma(\delta(x))dx}^{\text{misfit energy}} - \overbrace{\frac{K}{2}\int_{-L}^{L}\int_{-L}^{L} \rho(x)\rho(x')\ln|x - x'|dxdx'}^{\text{elastic energy}} \quad (1)$$

This model is fairly simple but predictively useful; it allows us to determine that the dislocation size depends only on fairly few smaller scale details. The fact that dislocations are the result of a stable trade-off between two energetic factors underlies the efficacy of the dislocation model in describing mesoscopic structure.

The expression thus derived is useful for predicting dislocation size but doesn't tell us about dislocation motion. This is because, despite its derivation, it's a continuum model which is invariant with respect to spatial translations. One reason dislocations are interesting is because their motion can absorb energy; if there were no resistance to motion then that would not happen. The replacement of the misfit energy integral with a sum over the energy at each atomic position resolves this problem.[5] This takes us to a model where the dislocation moves through a series of potential wells. For a dislocation to move on this model it must overcome the Peierls barrier. The stress required to overcome this barrier is known as the Peierls stress (σ_p) and may be derived from this model; it is written as in equation (2) where μ, ν are elastic constants, d is the interlayer distance between the planes along which dislocations "glide" (otherwise they "climb") and b is the Burgers vector (see figure 3).

[5] Note that the elastic energy still depends on a continuum assumption, though this can be corrected in the semi-discrete P-N model.

$$\sigma_p = \frac{2\mu}{1-\nu} \exp\left(-\frac{2\pi d}{b(1-\nu)} \right) \tag{2}$$

An interesting consequence of this equation is that the Peierls stress depends sensitively on d/b. For materials like ceramics which have low d/b, σ_p is too high for dislocation motion to prevent the material's fracturing. On the other hand, metallic systems have high d/b and thus are relatively ductile.

Having spelt out aspects of the derivation of the dislocation description, I turn to reductive explanation. I seek bottom-up explanations of the robustness of dislocation variables and their explanatory and predictive success. One upshot of the following analysis is that one can also use this bottom-up explanation to account for the limits of applicability of multiscale models that involve dislocations.

The dislocation description applies to a wide range of different underlying conditions. This can be seen by examining equation (1): the width of the dislocation core is derived by considering the competition of misfit and elastic energies. Determining this competition and minimising the total energy requires few details from the underlying system; as such the description is robust across a range of different values for other variables. However, importantly, the fact that dislocations are stable is determined by facts about the underlying lattice structure. Although the functions for elastic and misfit energy were expressed using continuous smaller scale variables, their derivation explicitly requires and depends upon reasoning about properties of the atomic lattice.

While a more detailed account of the processes which lead to robustness would bolster this reduction, the details given here should be sufficient to undermine the multiscale argument against worldly reductionism – these establish that the properties of the mesoscale structure are understandable from the bottom up. Many of the possible motions of the underlying atoms are irrelevant to the dislocation description, and salient features of dislocations are a fairly straightforward consequence of the structure of the lattice. As such, the processes which lead to the lattice formation and the equilibrium atomic bonding ensure that many of the atomic displacement variables are irrelevant.

One particular function of the dislocation model is to explain the ductility or brittleness of certain materials. This in turn depends on calculating the force required to effect dislocation glide. Crucial to understanding from the bottom up is that resistance to motion depends on the discreteness of the atomic lattice. Thus, the dynamics of the dislocation model is also a consequence of features of the lattice. This explanation works for a fairly wide range of smaller scale conditions – the value for the Peierls stress is dominated by d/b; thus, details of dislocation motion are insensitive to other underlying details. In other words, dislocation glide can be described without reference to many of the smaller scale details. This establishes the stability of the mesoscale description in terms of dislocations and their properties.

We can then consider the range of conditions of the underlying system over which dislocations are robust. It is required that the rest of the lattice is relatively well ordered: if too irregular then the dislocation will be indistinguishable from the movement of all the atoms around it. Lattices will be regular for a wide range of temperatures below the material's melting point.

The prospects for reductive explanation look good. We have a derivation of the robustness of the dislocation variables which then feed into the multiscale model. The processes which collude to make these variables effective for predicting the ductility of steel may be explained from the bottom up: they depend on details of the inter-atomic forces and the lattice structure.

We may reject eliminativism about dislocations because these are essential to a class of scientific explanations. Further reason to include dislocations in our ontology are that their dependencies are distinct from lower-level dependencies and screen off various atomic motions. See Franklin and Robertson (2021) for the argument that dislocations are, thus, emergent.

Multiscale methods are essential to accurate modelling of materials: for example, in the above analysis figures for elastic constants and generalised stacking fault energies may be empirical or may depend on modelling at other scales; moreover the concepts of brittleness and stress are generally defined at larger scales. But the fact of the utility of such multiscale techniques ought not to preclude our asking, where appeal is made to details at larger scales, whether such appeal may be explained reductively. As the discussion in this section has shown, such questions may be addressed even in the context of multiscale models. Moreover, the account in this section helps establish methodological non-reductionism: it would be a mistake for those scientists interested in predicting the ductility of steel to start with the atomic lattice and scale up assuming mesoscopic homogeneity, precisely because there is non-trivial robust mesoscale structure. As a consequence of such structure, methodological reductionism would go wrong in this context.

Were we to have been satisfied purely with Nagelian reduction that employed various idealisations, Batterman, Bursten, and Wilson's worries would remain unanswered. They establish that there is a complex and relevant mesoscale structure which determines the macroscopic properties of many materials. By offering a reductive explanation I have shown, from the bottom up, how and why such mesoscale structures are stable.

The dislocation model is appropriately embedded within a much larger framework and, if one wants to discuss reduction in the larger framework, one needs to make sense of widespread multiscale modelling. As my aim is not to defend eliminativism, I do not think that the use of such modelling practices is overly worrisome to the reductionist; nonetheless reductionists ought to engage in the difficult task of attempting to go as far as possible with reductive projects. Once we have established the details of the dislocation picture, this then ought to be related all the way up to the description of stresses applied to the macroscale steel structures. Of course I haven't gone that far, nor is the dislocation model discussed here the most detailed available; however, I have demonstrated that, even in contexts of multiscale dependencies, we can make progress towards evidencing worldly reductionism by offering localised reductive explanations.

5 Levels

One feature of the discussion in previous sections is worth noting: reduction usually involves reference to levels, where affairs at higher levels are reduced to those at lower levels, but thus far I have studiously avoided such terminology. This observation alone calls into question a certain anti-reductionist argument – that reduction requires a levels hierarchy which is incompatible with multiscale models. Notwithstanding that levels aren't required for reduction, the question I pose (but don't answer!) in this section is whether any adequate conception of levels appropriate to a multiscale world can be recovered.

Note that while I haven't talked about levels, reduction does have a preferred direction: reductive explanations account for less fundamental details in terms of more fundamental details. Greater fundamentality, in the contexts discussed here generally corresponds to smaller scales, but there are exceptions to this, most obviously in cosmological contexts. A full account of fundamentality would take more space than I have available, but I follow McKenzie (2019) in supposing that the fundamentality relation should be *a posteriori*.

Having said that reduction can proceed while avoiding levels talk, one might nonetheless think that levels play a useful role for philosophy of science, so we should think about whether or not any conception of levels can withstand the multiscale argument.

Levels, as used in science and philosophy of science are often taken to have three salient features that are of interest for the present discussion. First, levels contain the resources to explain and predict much of what goes on at that level. That is, goings-on at a level are commonly explained or predicted by facts or details at the same level – many intra-level explanations and predictions are available. Second, levels are linked to a fairly narrow range of spatial and temporal scales. Third, different levels do not cross-classify entities, whereby a set of entities would both share a level and be found on different levels.

Many will find these three features of levels to be somewhat intuitive, as can be seen in many well-known accounts ranging from Oppenheim and Putnam (1958) to List (2018). However, the fact that many of our best scientific models are multiscale generates a conflict between the first feature on the one hand, and both the second and third features on the other. That's because multiscale models are required for a great many predictions and explanations, as such, fulfilling the first criterion implies that some levels are multiscale. But multiscale levels will be spread over a wide range of spatial and temporal scales, and different multiscale models will, in many cases, lead to a cross-classification of entities as members of different levels.

The case study in §4, and, in particular, figure 2, provide a nice illustration of these issues. Predicting and explaining the brittleness of steel requires an understanding of the properties and dynamics of entities from the nanometre to the centimetre ranges. If these were all to be at a single level, not only would this violate the narrow range of scales feature of levels, but it would lead to a cross-classification with, for example, the levels used to explain the thermal conductivity of steel.

I do not take such multiscale models to undermine the reductionist project, because traditional conceptions of levels aren't required in order to proceed with reductive explanation. For example, the explanation of the robustness of the dislocation variables is in terms of particular arrangements of the atomic lattice. Such arrangements will not, in general, exhibit explanatory or predictive closure. However, they do allow for an account of why the dislocation aspect of the multiscale model works so well.

Consequently, although I defend a kind of worldly reductionism, I take this to be compatible with the expunging of the levels concept from philosophy and science. It may well be that the three features of levels are so entrenched, that no alternative conception can be developed which is adequate to scientific predictive and explanatory practice. In this respect I have sympathy for Potochnik (2017, p. 185) who suggests we "jettison talk of levels entirely", although I disagree with her claims that reductionism should go the same way.

On the other hand, I don't think that an eliminativist response is the only one available. While levels have traditionally been taken to satisfy all three features, could an appropriately attenuated conception of levels be recovered? One could, for example, claim that levels describe processes at a restricted range of spatial scales and don't cross-classify, but that they are not even approximately predictively or explanatorily closed. Alternatively, one could give up on the restricted range of scales and no cross-classification requirements but insist on effective predictive and explanatory closure. This option is explored by Potochnik (2021), who suggests that temporal, spatial, mereological, etc. conceptions of levels (or 'nests') are appropriate to different scientific projects.

While I'm sympathetic to this latter option, it's worth noting that it would involve a great many more levels than might be commonly expected in the philosophy of science literature. This account of levels will certainly allow for the recovery of some of the standard usage of the concept in science, but the cost is that levels are so ubiquitous that the concept may seem fairly empty to many. Therefore, one who pursued this option might wish to add additional criteria in order to satisfy the idea that levels aren't absolutely everywhere.

It's my view that aspects of this question are terminological – although I take questions of reductionism to be metaphysically substantive, whether one uses ‘levels’ in one way or another is less important. If levels were required for the reductionist project then I would take these problems to be rather serious. However, it seems to me that we do very well in the philosophy of science without resolving the contradiction among assumed features of levels.

6 Conclusion

Accurate scientific descriptions of the world involve a great deal of complexity. And science grows ever more complex with ever more caveats to the applicability of its models. Such trends are part of the motivation for the philosophers considered in this chapter. If, rather than growing more unified, the complexity of science is increasing, how could reductionism be maintained?

That question is behind the multiscale arguments considered above. I think that such arguments deserve more attention than they have received in the literature. And I’ve claimed that those arguments establish, firstly, that methodological reductionism is false, and, secondly, that levels are either everywhere or nowhere.

However, I also claimed that the view of reductionism assumed by defenders of the multiscale argument tends to be overly simplistic. Aside from methodological reductionism, they focus on a view that makes unwarranted idealisations. For example, they emphasise that putative reductions are predicated on homogeneity assumptions which, in many circumstances, drastically misrepresent the target systems. When solids are out of equilibrium or there is mesoscopic structure we need to take a more nuanced approach to describing the world. I have argued that such nuanced approaches are consistent with worldly reductionism, evidenced by localised reductive explanations.

As a consequence, I demonstrated that the increasing complexity of science is compatible with reductionism so understood. Nonetheless my argument does not establish worldly reductionism – it’s still an empirical question whether or not this should be accepted. Scientific investigation is required to establish if reductive explanations are available in any particular context.

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