Studies in History and Philosophy of Biological and Biomedical Sciences 61 (2017) 20–34

Contents lists available at ScienceDirect

Studies in History and Philosophy of Biological and Biomedical Sciences

journal homepage: www.elsevier.com/locate/shpsc

# Biology meets physics: Reductionism and multi-scale modeling of morphogenesis

Sara Green [a,*], Robert Batterman [b]

[a] *Department of Science Education, University of Copenhagen, Øster Voldgade 3, 1350 Copenhagen, Denmark*
[b] *Department of Philosophy, University of Pittsburgh, 1028-A Cathedral of Learning, Pittsburgh, PA 15260, USA*

ARTICLE INFO

*Article history:*
Received 18 January 2016
Received in revised form
8 December 2016
Available online 23 December 2016

*Keywords:*
Multi-scale modeling
Boundary conditions
Explanatory reduction
Developmental biology
Biomechanics
Reductive explanations

ABSTRACT

A common reductionist assumption is that macro-scale behaviors can be described “bottom-up” if only sufficient details about lower-scale processes are available. The view that an “ideal” or “fundamental” physics would be sufficient to explain all macro-scale phenomena has been met with criticism from philosophers of biology. Specifically, scholars have pointed to the impossibility of deducing biological explanations from physical ones, and to the irreducible nature of distinctively biological processes such as gene regulation and evolution. This paper takes a step back in asking whether bottom-up modeling is feasible even when modeling simple physical systems across scales. By comparing examples of multi-scale modeling in physics and biology, we argue that the “tyranny of scales” problem presents a challenge to reductive explanations in both physics and biology. The problem refers to the scale-dependency of physical and biological behaviors that forces researchers to combine different models relying on different scale-specific mathematical strategies and boundary conditions. Analyzing the ways in which different models are combined in multi-scale modeling also has implications for the relation between physics and biology. Contrary to the assumption that physical science approaches provide reductive explanations in biology, we exemplify how inputs from physics often reveal the importance of macro-scale models and explanations. We illustrate this through an examination of the role of biomechanical modeling in developmental biology. In such contexts, the relation between models at different scales and from different disciplines is neither reductive nor completely autonomous, but interdependent.

## 1. Introduction

An important reductionist assumption is that multi-scale systems can be described “bottom-up”, if only sufficient details about the states of the components are available. Historically, this assumption has been debated in philosophical discussions about whether biology is reducible to physics. The positivist ideal of a unity of science pictured the relations between scientific disciplines in a “layer-cake” hierarchy where theories from respective disciplines target a specific level or scale of phenomena (Oppenheim & Putnam, 1958).[1] Physics was considered the most fundamental “model discipline” targeting the lowest organizational level, and progressive reduction was considered an important aspect of scientific development (see also Hüttemann & Love, 2016).

The view that an ideal or fundamental physics would be sufficient to explain all macro-scale phenomena has been met with criticism from philosophers of biology. Scholars have stressed the irreducibility of biological features, such as gene regulation or evolution, and argued that biological explanations are irreducible to physical laws and principles (e.g., Bechtel & Richardson, 1993; Bertalanffy, 1969; Burian, Richardson, & Van der Steen, 1996; Dupré, 1993; Machamer, Darden, & Craver, 2000; Mayr, 1988, 2004; Winther, 2009). These contributions have offered important insights to distinctive features of living systems and biological research. However, an important question that is rarely addressed is whether the ideal of progressive reduction of higher-level explanations is supported in physics, i.e., in the discipline that was taken as a model for the reductionist ideal. We argue that lessons from multi-scale modeling offer resistance to reductionism which cross-cut discussions in philosophy of biology and philosophy of physics.

---

* Corresponding author.
*E-mail address:* sara.green@ind.ku.dk (S. Green).

[1] We use the term "level" when referring more explicitly to part-whole relations in a hierarchical description or a functional system (demarcated by boundaries such as the cell membrane), but we prefer the term "scale" when referring to spatial scaling because biological "levels" are often not straightforwardly distinguished (see also Noble, 2012). For a more detailed discussion of biological levels and part-whole relations, see (Kaiser, 2015).

http://dx.doi.org/10.1016/j.shpsc.2016.12.003
1369-8486/

We focus on what Mayr (1988) calls *explanatory reduction,* which involves explaining phenomena at higher scales in terms of processes at lower scales or levels of organization (e.g., molecules or genes).[2] Other important aspects of reductive explanations are that they typically analyze biological parts in isolation from their original context and give explanatory priority only to factors internal to the system (Kaiser, 2015). In recent discussions on explanatory reduction it is debated whether the constitution of macroscale systems by microscale components allows the researcher to explain the system only with reference to properties of the lower scale constituents (Brigandt & Love, 2012). For instance, although the composition of polypeptides is reducible to a sequence of amino acids, it has been argued that it is not possible to explain protein folding from physical laws and knowledge about amino acids alone (Love & Hüttemann, 2011). The prospect of reductive explanations in biology and physics is, however, an ongoing issue of debate.

This paper sheds further light on the debate on reductionism by clarifying how lessons from multi-scale modeling in both physics and biology offer resistance to the idea that multi-scale systems can be modeled and explained "bottom-up". Secondly, unlike what one might expect from physical science approaches, we argue that work within biomechanics brings attention to the problems of understanding biological processes and parts in isolation from their original context in cells or tissue structures (Kaiser, 2015). Thus, rather than enforcing reductionism, physical science approaches can help reveal the limitations for reducing explanations in developmental biology to genetics. Accordingly, we argue that the role of physical science approaches in biology with respect to reductionism should be revisited.

Our aim is to bring attention to the *tyranny of scales problem* that has so far mainly been discussed in the context of physics (Batterman, 2012; Oden, 2006; see however; Lesne, 2013).[3] The problem refers to the scale-dependency of physical behaviors that presents a hard challenge for modeling and explaining multi-scale systems. No single mathematical model can account for behaviors at all spatial and temporal scales, and the modeler must therefore combine different mathematical models relying on different boundary conditions. Fig. 1 illustrates the interplay of models describing processes at different scales. The expression $h = H(r)$ indicates how macroscale features and properties arise from the collective behavior of microscale variables.[4] However, the expression at the left side of the figure, $r = R(h)$, indicates how microscopic elements are affected by macroscopic variables $h$ through the influences of constraints, effective inputs, and boundary conditions.

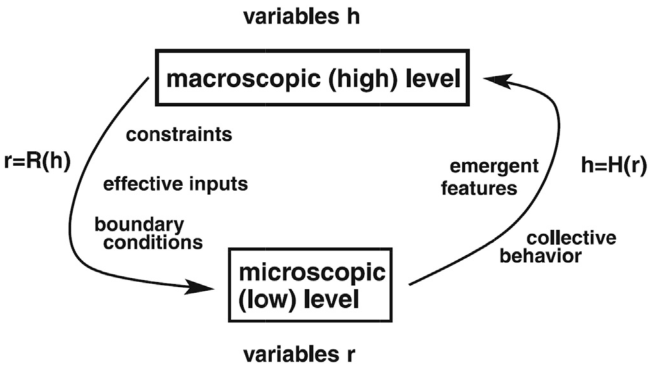

**Fig. 1.** Illustration of the interplay of "microscopic" and "macroscopic" modeling. From *Acta Biotheoretica*, Multiscale analysis of biological systems 61, 2013, p. 14, A. Lesne, reprinted with permission of Springer.

*Constraints* in this context are understood broadly as conditions that limit and enable certain behaviors, such as tissue stiffness that influences the bending properties of biological structures (see also Hooker, 2013). Modelers often express physical constraints mathematically as *boundary conditions*, i.e., as definite mathematical parameters. Boundary conditions are often indispensable to the modeling procedure, because the equations cannot be solved without imposing limits on the domain of the model. In this paper we describe how the scale-dependent behavior of physical and biological systems forces researchers to combine different experimental and representational strategies targeting specific scales.[5] We illustrate this with examples from both physics and biology.

Since we are drawing on contemporary cases of multi-scale modeling, the reductionist may object that all we point to are practical limitations of *current* science. That is, one may object that it *in principle* should be possible to explain macro-scale systems with reference only to lower scale molecular details. The specific methodologies will indeed develop and change over time. However, it should be noted that the need to combine different approaches arises due to the fundamental challenge that concepts used to characterize systems and their behaviors can change as one changes scale: They are *multi-valued* across scales (Wilson, 2012). For example, not only does the concept of "surface" change as one moves toward the nanoscale (where there is typically more "surface" than bulk material) but so do the kinds of concepts we need to characterize the dominant behaviors at the different scales (Bursten, 2015; see Section 2).[6] Against the background of this complexity, we find appeals to in principle derivations empty without suggestions of how to make such inferences (see also Batterman, 2016). Rather than logical possibilities for explanatory reduction, this paper is concerned with the challenges faced in

---

[2] Explanatory reduction is distinguished from *Constitutive reduction* and *Theory reduction*. Constitutive reduction (also called ontological reduction or (token) physicalism) refers to the acceptance that biological systems are nothing but physical-chemical systems. *Theory reduction* considers the possibilities of reducing (in a logical sense) higher-level theories in special sciences to more fundamental ones (cf., Rosenberg & Arp, 2010; Sarkar, 1998; Schaffner, 1993; Winther, 2009). More recently, philosophers of biology have discussed this kind of reduction in terms of explanatory relevance, e.g., whether the explanatory power in biology is constituted by physico-chemical principles or biological mechanisms (Machamer et al., 2000; Weber, 2008). A separate kind of reductionism, *methodological reductionism,* considers heuristic strategies that simplify the problem space for scientific analysis (Bechtel & Richardson, 1993; Brigandt & Love, 2012; Green, 2015).

[3] To be sure, mechanistic accounts in philosophy of biology (e.g., Bechtel & Richardson, 1993; Machamer et al., 2000) have taken issue with reductionism in arguing against reducibility of biology to physics and in allowing for interlevel explanations. However, mechanistic accounts have so far not attended to the challenges for reductionism provided by the scale-dependency of physical behaviors (see Skillings, 2015 for further discussion).

[4] As indicated on the figure, such features are often labelled as "emergent". We shall not go into the question about emergence in this paper (see Boogerd, Bruggeman, Richardson, Achim, & Westerhoff, 2005 for a detailed discussion of emergence in biology).

[5] This paper focuses on the adequacy of explanatory reduction through a demonstration of the requirement of multiple models. As an anonymous reviewer pointed out, it is possible to agree with the inadequacy of explanatory reduction but argue that a single higher-level model is adequate. Our account would offer resistance also to a monistic anti-reductionist view of this kind but we do not develop such an argument in the paper.

[6] Already Galileo (*Discorsi*, 1638) pointed to the importance of scale when considering the disproportional relation between the minimal thickness of bone structures and animal size. Biologists investigating morphological constraints on animal form have similarly stressed that macroscale physics does not apply to microorganisms. At this scale, gravity is a weaker force whereas surface properties and Brownian motion are central parts of the analysis (see e.g., Purcell, 1977; Vogel, 2009). Similarly, the models most useful to model molecular behavior are rarely the most useful for modeling tissues. See Section 2 for further clarification.