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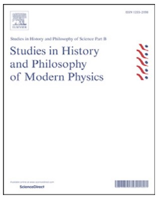
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Complexity as a contrast between dynamics and phenomenology

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1. Introduction

Since its inception in the late 1980s, complexity science has evolved into a well-established and highly popularized area of science (e.g., for a description of the field's history, Mitchell, 2009). The ascent of the field has been accompanied a number of foundational claims, ranging from a redefinition of the arrow of time (e.g. Davies, 2003) to the often quoted slogan 'more is different' by Anderson (1972). Such foundational claims have also generated much philosophical debate.

Complexity is universally taken to be a property that characterizes a class of dynamical systems. However, the question of how this property should be defined, i.e. which criteria need to be fulfilled for the label 'complex' to be bestowed on a system, has remained unresolved. During the last thirty years, a large number of different complexity definitions have been proposed: Lloyd (2001, p. 7) lists forty-two different definitions of complexity and considers this collection a 'non-exhaustive list'. Responses to this difficulty in finding an unequivocal definition of the core concept of the field have been different among practitioners and philosophers: while complexity scientists have maintained that a single formal definition is unnecessary and that the labelling of systems as being complex can often be underdone intuitively (e.g. Gell-Mann, 1995; Gershenson, 2008), philosophers have been more concerned with identifying which properties are necessary for a system to be called 'complex' (e.g. Zuchowski, 2012; Ladyman, Lambert, & Wisener, 2013). The driving force behind such philosophical accounts is usually not just the development of a better understanding of the concept itself but also its demarcation from related concepts like chaos and randomness. However, even philosophers usually do not aim at deriving a single, authoritative definition of complexity but rather at the identification of sets of criteria that have been associated with the label 'complex' (Ladyman et al., 2013) or at the derivation of minimal definitions, which deliberately highlight the lack of agreed upon criteria (Zuchowski, 2012).

In this paper, I will take a novel approach to the investigation of complexity definitions that – in addition to identify general criteria used in complexity definitions – focuses on the relationship between these criteria and uses these relationships to derive a minimal definition of the concept of complexity. Thereby, I will use a tiered analytical framework (section 1.1, Fig. 1) that distinguishes between a general concept, which can be defined through a minimal definition; different definitions associated with this concept; criteria that are used in these definitions; and technical embodiments of these criteria. My results will be illustrated on three well-known models in complexity science (section 2): the CA110 (section 2.1); the Bak-Sneppen model (section 2.2); and the logistic equation (section 2.3).

My analysis can be visualized roughly as an ascent through the different tiers of the analytical framework. Firstly, in section 3, I will argue that the vast majority of complexity definitions can be viewed as requiring different combinations of different technical embodiments of five core criteria for the diagnosis of complexity: the three dynamical criteria of the existence of many components (section 3.1.1), determinism (section 3.1.2) and indeterminism (section 3.1.3); and the two phenomenological criteria of regularity (section 3.2.1) and irregularity (section 3.2.2).

Secondly, in section 4, I will then use my identification of the criteria for the diagnosis of complexity to analyse three different complexity definition, each of which can be seen as indicative of a class of similar definitions. In particular, I will show that the determinism-based definition of complexity by Wolfram (1984, 2002) requires fulfilment of the criteria of determinism, regularity and irregularity (section 4.1); that the indeterminism-based definition by Ladyman et al. (2013) requires fulfilment of the criteria of the existence of many components, indeterminism and regularity (section 4.2); that the inclusive definition by Goldenfeld and Kadanoff (1999) requires fulfilment either of the criteria of determinism and irregularity or of indeterminism and regularity (section 4). My analysis enables a de-tailed comparison of these definitions and it will become apparent that the determinism- and indeterminism-based definition are exclusive of one another, i.e. there is no overlap between their extensions. In contrast, the extension of the inclusive definition includes the extensions of both

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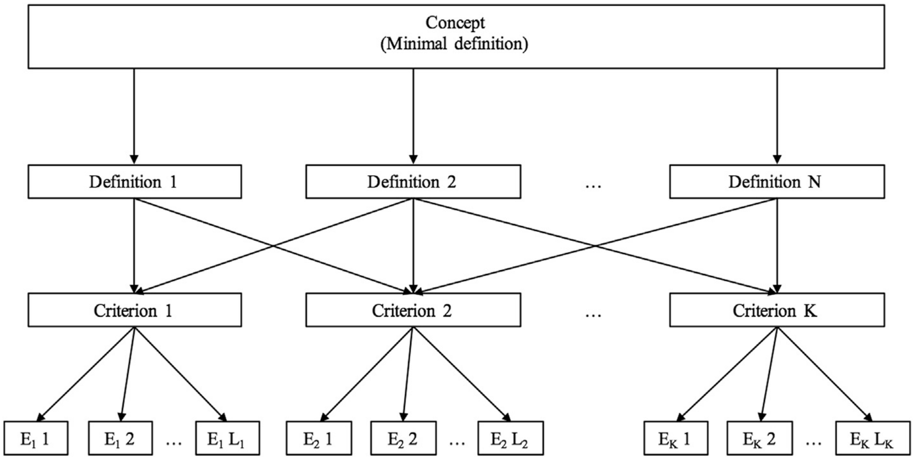

Fig. 1. Relationships between concepts, definitions, criteria and embodiments (abbreviated as E). The total number of definitions, criteria and embodiments are denoted by N, K and L, respectively.

other definitions. Furthermore, I will show that the determinism- and indeterminism based definitions both exclude chaotic systems while the inclusive definitions allows these systems to be additionally classified as complex. This will also be borne out by an application of these definitions to the three case studies.

Thirdly, in section 5, I will use the results from my analysis of different complexity definitions to provide a minimal definition of complexity, i.e. to provide a description of the concept of complexity that underlies all of these definitions. The minimal definition will be based on a property shared by all analysed definitions: they all require combinations of contrasting dynamical and phenomenological criteria. In particular, all definitions require either the dynamical criterion of determinism in conjunction with the phenomenological criterion of irregularity or the dynamical criterion of indeterminism in conjunction with the phenomenological criterion of regularity. Furthermore, I will show that two of the most prevalent metaphorical descriptors of complexity, 'being between order and chaos' and 'self-organisation' can also be interpreted as encapsulations of specific dynamics-phenomenology contrasts, namely the one specific to the determinism- and the indeterminism-based definition, respectively. Accordingly, I will propose that the concept of complexity should be (minimally) defined as the existence of dynamics-phenomenology contrasts. Additionally, I will show that the dynamics-phenomenology contrast that is reflected in the definitions and descriptors can be viewed as a specific kind of epistemological emergence (section 5.2).

The realisation that it is this contrast between (deterministic/indeterministic) dynamics and (regular/irregular) phenomenologies that is articulated in all complexity definitions and the major metaphorical descriptors of the field, and therefore forms the conceptual heart of complexity science, constitutes the main result of my analysis. In light of this result, the coexistence of many different complexity definitions can be viewed as providing a means of identifying this core concept in different classes of systems. While the relative merits of different definitions can still be argued, their coexistence should therefore not be seen as a sign of deep conceptual divisions but as a means of highlighting one shared concept, i.e. the existence of a contrast between dynamics and phenomenology, in many different models. Accordingly, my analysis also offers a way to demarcate the field of complexity science itself: namely, as the field of science concerned with the study of systems that display such contrasts between their dynamics and phenomenologies. Since the concept of complexity can be interpreted as a kind of epistemological emergence, this also implies that emergence is indeed part of the foundations of complexity science.

In addition to those conceptual results about the foundations of complexity science, my analysis also leads to the clarification of a number of concepts, definitions and metaphors in complexity science. It therefore results in a clear exhibition of the epistemic structure of the field, i.e. it allows for a conceptual sharpening of terminology and reveals the relationships of different terms with each other. Accordingly, I hope that my work here also contributes to the terminological tidying of complexity science that has been requested by several authors (e.g. Frigg, 2003; Horgan, 1995). However, since this analysis is an exercise in rational reconstruction, I do not claim that it is the only viable interpretation – nor that it always captures the initially intended meaning of a concept in all historically relevant nuances – or that the analytic framework I use is the only possible one for the analysis of scientific definitions. Instead, I hope that merits of my conceptual reconstructions will be evident in the clarity with which they expose the concept underlying different complexity definitions and the relationships these definitions have with each other.

In the following two subsections, I will briefly review the frameworks and concepts on which my analysis in sections 3–5 will be based: the tiered framework for the analysis of definitions (section 1.1); and the concept of emergence, which – relative to the wealth of material available on this topic – will only be reviewed very briefly (section 1.2).

1.1. *Concepts, definitions, criteria and embodiments*

The coexistence of many different definitions of a core concept is not unique to complexity science: similar constellations can be found for a large variety of terms, e.g. 'partnering' (Nystroem, 2005); 'sensitivity' (Mencattini & Mari, 2015); 'synergy' (Berthoud, 2013) and 'chaos' (Zuchowski, 2017). The conceptual frameworks used to analyse the relationships be-tween the overarching concept and the different definitions are usually based on a further decomposition of the latter into different 'components' (e.g. Nystroem, 2005) or 'criteria' (e.g Zuchowski, 2017). I will adopt the latter nomenclature. In a third level of analysis, the criteria required by a given definition can be further decomposed into technical embodiments, i.e. formal specifications of a given criterion that allow a quantitative measurement in a given set of scenarios (Mencattini & Mari, 2015; Zuchowski, 2017, e.g.). From such a compositional analysis of a concept into separate definitions,

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