On the nature of cross-disciplinary integration: A philosophical framework

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Abstract

Meeting grand challenges requires responses that constructively combine input from multiple forms of expertise, both academic and non-academic; that is, it requires cross-disciplinary integration. But just what is cross-disciplinary integration? In this paper, we supply a preliminary answer by reviewing prominent accounts of cross-disciplinary integration from two literatures that are rarely brought together: cross-disciplinarity and philosophy of biology. Reflecting on similarities and differences in these accounts, we develop a framework that integrates their insights—integration as a generic combination process the details of which are determined by the specific contexts in which particular integrations occur. One such context is cross-disciplinary research, which yields cross-disciplinary integration. We close by reflecting on the potential applicability of this framework to research efforts aimed at meeting grand challenges.

Keywords

Integration, interdisciplinarity, transdisciplinarity, grand challenge, reduction

1. Introduction

Research efforts around the world are increasingly organized around *grand challenges* (Brooks et al., 2009; Efstathiou, this issue). Classifying a problem as a "grand challenge" indicates that (a) the problem is exceedingly complex—either as a fundamental problem "with broad applications" (e.g., advanced new materials—NSF, 2011, p. xiv) or as a socio-technical problem manifesting at various scales (e.g., poverty, climate change)—and (b) there is interest in mobilizing political and financial will behind research aimed at a solution. Significant global attention has been paid to grand challenges involving the biological and biomedical sciences, including maternal health and child mortality (WHO, 2014), food security (EUFPRI, 2014), and sixteen challenges related to global health identified by the Gates Foundation in partnership with

the NIH (BMGF/NIH, 2013). Each of these efforts is associated with substantial funding for research conducted by "an international community of scientists towards predefined global goals with socio-political as well as technical dimensions" (Brooks et al., 2009, p. 8).

Given their complexity, meeting grand challenges will require multiple forms of expertise. At a minimum, experts from multiple academic disciplines are necessary; typically, however, a broader range of expertise is needed, including stakeholder, private sector, and governmental expertise. Further, it will be important that the complexity of a challenge be met with complexity in response. That will require the constructive combination—or *integration*—of perspectives. Meeting grand challenges, then, requires cross-disciplinary[1] responses that constructively combine multiple forms of expertise, or what we shall refer to as *cross-disciplinary integration*. But this motivates a prior question: just what is cross-disciplinary integration?[2]

In this paper, we supply a preliminary answer to this question. As we note below, the centrality of integration to cross-disciplinary research has made it a topic of investigation across multiple literatures, but few authors offer reviews that integrate these distributed discussions. Philosophy of biology stands out as a literature in which integration has received sophisticated treatment (e.g., Brigandt 2013), and the same can be said for the literature on cross-disciplinarity. We detail prominent accounts of cross-disciplinary integration found in these literatures, noting similarities and differences. After addressing methodological preliminaries, we outline a framework that integrates the insights of these accounts. We close by reflecting on the potential applicability of this framework to research efforts aimed at meeting grand challenges.

2. Accounting for integration

In this section, we take an initial step toward an integrated review by providing information about several prominent accounts of cross-disciplinary integration. First, though, a few words are in order about the selection of accounts and the organization of this discussion. There are multiple, overlapping literatures in which ostensibly relevant notions of integration arise: cross-disciplinarity, science of team science, philosophy, communication studies, management, education, and others.[3] As we noted above, we limit our survey in this short article to two literatures: cross-disciplinarity and philosophy of biology. The cross-disciplinarity literature stands out because the notion of integration is a central tool for much work in this area; further, by exploring integration in a more abstract way, this literature provides a "view from above" on integration as it functions in a wide range of cross-disciplinary activities. For a "view from

[1] We use 'cross-disciplinary' as a cover term for both interdisciplinary and transdisciplinary activity. When the context requires more specificity—as in section 2—we will use 'interdisciplinary' to mean the integrative combination of disciplinary perspectives and 'transdisciplinary' to mean the integrative combination of disciplinary and stakeholder perspectives. For discussion of these modes of research, see Klein (2010).

[2] This is consonant with O'Malley's (2013) call for identifying "what is meant by [integration] and whether different interpretations can be combined coherently into a general use of the concept" (p. 552).

[3] See Klein (2013) for consideration of integration in each of these domains, set in the context of concern about communication across disciplines and professions.

below", we turn to philosophy of science, and specifically, philosophy of biology. Philosophers of science have long reflected on integration, or at least integration-like phenomena (e.g., Oppenheim & Putnam, 1958), but contemporary philosophy of biology stands out for its close and explicit attention to integration across biological disciplines and at multiple scales (O'Malley, 2013). Together, these literatures provide views on cross-disciplinary integration in both theory and practice.

We begin by considering the views of integration developed by a number of contributors to each literature. The views we have selected are prominent within their respective literatures, and they also illustrate a range of approaches to integration that have been developed in each. We then note similarities and differences among the views, focusing on the major points of difference that emerge.

2.1 Integration in cross-disciplinarity

The theorists we consider in this section—William Newell, Allen Repko, Julie Thompson Klein, Gabriele Bammer, and Matthias Bergmann and colleagues—can be classified as *integrationists* because they regard integration as central to cross-disciplinary activity.[4] Klein, for example, observes that "[i]ntegration is widely regarded as the primary methodology of interdisciplinarity" (Klein, 2012, p. 283), while Bergmann et al. (2012) remark that "the importance of integration work … can hardly be overestimated for transdisciplinary research" (p. 42). In a similar spirit, Newell asserts, "By definition, interdisciplinary study draws insights from relevant disciplines and integrates those insights into a more comprehensive understanding" (Newell, 2001, p. 2).[5] A widespread commitment to integration as a central feature of cross-disciplinarity, however, does not entail agreement on just what integration is. Newell remarks that it is "not even clear … exactly what is *meant* by integration" (Newell, 2001, p. 19), while Repko contends that "the lack

[4] See Repko (2007) for details. Klein (1990) is an early source for this idea and Repko (2012), ch. 9, provides a more general discussion of the integrationist position. Bammer (2013) goes beyond interdisciplinarity but the core commitment to integration remains the same. Bergmann et al. (2012) is devoted to working out integration methods, strategies, and supportive aspects for use by transdisciplinary researchers. Repko contrasts integrationists with what he calls *generalists*, such as Lattuca (2001) and Moran (2002), who de-emphasize the role of integration in characterizing interdisciplinarity while emphasizing the roles played by questions or dialogue. A more detailed account of integration in cross-disciplinarity would contrast its methodological role with the methods employed by theorists like Lattuca and Moran, but that is beyond the scope of this article.

[5] For a contrary view, see Holbrook (2013). Holbrook associates integration with a mode of interdisciplinary communication that emphasizes inter-translatability and communicative rationality under the banner of the "Klein-Habermas thesis". The other modes of interdisciplinary communication he describes do not involve integration, viz., acquiring a second disciplinary language understood to be incommensurable with your first, or invention of a new language via "strong communication" (p. 1876). We believe that Holbrook's conception of integration is too limited and fails to accommodate the essentially integrative aspects of the other modes of interdisciplinary communication. Unfortunately, we don't have the space here for full consideration of his critique.

of clarity on precisely *what* to integrate and *how* to integrate" has been the "Achilles' heel of interdisciplinarity" (Repko, 2007, p. 7).

With a view to rectifying this situation, Newell (2001, 2007), and Repko (2007, 2012) follow Klein (1990) in developing systematic, step-by-step accounts of how to *do* interdisciplinarity, with integration appearing in the later steps (Newell 2001; Repko 2012). Set in the context of interdisciplinary studies, these accounts are designed to leverage cognitive insights developed in helping individuals (in particular, students) achieve integrative research success. As an illustration of this approach, consider the algorithmic accounts put forward in Newell (2001, 2007) and Repko (2007, 2012). Both are set against a background of disciplinary conflict and tension. Integration, Repko tells us, "arises out of conflict, controversy, and difference. Without them, integration would be unnecessary" (2012, p. 294). Interdisciplinary success is achieved only when disciplinary investigators attain common ground on which "conflicting insights … can be integrated" (Repko, 2012, p. 268). But Newell cautions, "The goal of creating common ground is not to remove the tension between the insights of different disciplines, but to reduce their conflict" (2007, p. 260). Conflict reduction is facilitated by various techniques that link disciplinary concepts and assumptions, including "redefinition, extension, organization, and transformation" (Ibid., p. 258).On the algorithmic approach, then, integration is a type of stepwise combination that generates a more comprehensive whole comprising disciplinary parts that have been rendered harmonious by various conceptual techniques.

Some integrationists deny that there is something in common to every instance of integration. Klein (2012), for example, develops a comprehensive account of cross-disciplinary integration that reveals the operation of several general principles, one of which is the "Principle of Variance", according to which there is "*no universal formula for integration*" (p. 293). This principle derives from the high degree of variation found across cross-disciplinary projects, including their themes, goals, scope, and complexity. Not surprisingly, then, she rejects the algorithmic approach championed by Repko and Newell (and her earlier self), insisting that the integration process is "heuristic and constructivist at heart" (p. 296).[6] As she understands it, cross-disciplinary integration unfolds in an iterative, "back and forth" way that can be supported by combining cognitive and social elements into a "foundation for integration" (p. 294). Drawing on Habermas's notion of *communicative rationality*, she identifies intersubjective understanding, or "making sense together", as an important goal in this space (p. 295).[7] Thus Klein (2012) adds consideration of the collaborative and social to the individual and cognitive emphasized by Newell and Repko.

Bergmann et al. (2012) focus exclusively on transdisciplinary research, which they take to be a

[6] The constructivism here is that of Piaget, emphasizing the construction and adjustment of integrated meaning that reflects experience in a dynamic, socio-cultural context. Boix Mansilla (2010) develops a view in this spirit, viz., a "pragmatic constructionist" account of integration as a process that aims to produce "a system of thought in dynamic equilibrium" (p. 295). Like Newell and Repko, Boix Mansilla emphasizes individual cognition, but unlike them sets aside the stepwise approach in favor of a more neo-Piagetian, contextual model that involves four cognitive processes: "establishing purpose", "weighing disciplinary insights", "building leveraging integrations", and "maintaining a critical stance" (p. 298).

[7] For discussion of this part of her view, see Holbrook (2013).

way of acquiring knowledge that promises both "new options for solving societal problems" and new "interdisciplinary approaches and methods" (p. 14). Although they present an algorithmic approach to integration, the three phases they describe—identifying the problem and translating it into scientific questions, conducting integrative research, and disseminating and evaluating results—are presented at an abstract level that leaves room for substantial recursion and adjustment. The contextual nature of transdisciplinary integration is reflected in the fact that integration manifests differently during different stages of the research process, from reconciliation of the inputs to be integrated (p. 28) through critical monitoring of research results (p. 41). Much of their work is devoted to developing methods and strategies for achieving integration along three dimensions: communicative, social, and cognitive (p. 45).[8] Implementation of these methods and strategies varies according to the type of integration, e.g., integration of social with natural sciences, but they are intended for the full range of transdisciplinary research objectives.

Relying on a comparative methodology that relates many literatures, Bammer (2013) makes the case for creating a new discipline, Integration and Implementation Sciences, as the home for integrative applied research, a style of research that involves

> … experts from several disciplines plus stakeholders working on a common complex real world problem in a way that not only brings together their insights but also deals comprehensively with unknowns, all in order to support policy and practice change. (Bammer, 2013, p. 9)

Integration is a central feature of this discipline, which includes cross-disciplinary research but extends beyond it to include implementation practices. Bammer distinguishes integration from *synthesis*, which she takes to be "the bringing together of disciplinary and stakeholder knowledge", a combination in which different "disciplinary and stakeholder perspectives" must be "harnessed as part of the knowledge synthesis" (p. 42). By contrast, integration is "the combination of the synthesized knowledge with a considered response to the remaining unknowns about the problem" (2013, p. 18).[9] Both of these types of combination can be planned, Bammer argues, and she supplies a "five question framework" intended to structure such planning (p. 20). For Bammer, as for the others, integration is a kind of *combination*, but she interprets it somewhat differently than other integrationists. For her, it involves combining the known with the responses to the unknown, whereas for other integrationists it seems to involve combining various perspectives on what is known.

These accounts of cross-disciplinary integration describe how to achieve integration and what integration achieves for us. The integrative process consists in activities that can be structured by various techniques, yielding outcomes that advance cross-disciplinary research. These accounts agree in taking integration to be *contextual*, i.e., dependent for its specific form on the context in which it is pursued, and *purposive*, i.e., a process intentionally implemented by researchers in

[8] Compare this with Pohl et al.'s (2008), p. 417, discussion of the twelve "primary ways of integrating" within a transdisciplinary research context, derived from crossing four "ideal" means of integration with the three forms of collaboration.

[9] We argue below that *integration* and *synthesis* (in Bammer's senses) are both types of integration that differ according to what is integrated.

pursuit of objectives. But there are also "faultlines" along which the accounts differ, highlighting the fact that one can be an integrationist without agreeing on what integration is. First, there are those (e.g., Newell, Repko, early Klein, and to some extent Bergmann et al.) who take integration to be *algorithmic*, achievable in a wide range of contexts by implementing fixed steps in an orderly fashion, while others (e.g., Bammer and the later Klein) take integration to be more *heuristic*, varying dramatically across contexts in ways that require constructivist or "ecological" thinking (Huutoniemi, 2014).[10] Second, while all discuss a cognitive dimension, some (e.g., the later Klein, Bammer, Bergmann et al.) take integration to be framed by additional dimensions, such as social and communicative dimensions. This second faultline runs parallel with a third separating accounts that see integration as primarily an individual phenomenon from those that see it as collaborative as well. Finally, there are those, such as Newell and Repko, who emphasize integration between research disciplines and those, like Bergmann et al., who focus on integration as involving societal, or transdisciplinary, contributions that cannot be reduced to disciplinary concepts, assumptions, or theories. (See Table 1.)

[Table 1 here]

2.2 Integration in philosophy of biology

The accounts considered in Section 2.1, while informed in some cases by concrete examples (e.g., Repko, 2012) and case studies (e.g., Bergmann et al., 2012), all conceive of integration abstractly, in a way that crosses contexts even if its specific instances are highly context-sensitive. We now turn to a literature in which accounts of integration are embedded in a more concrete cross-disciplinary matrix, the disciplines of biology. This literature is noteworthy for its close, reflective consideration of cross-disciplinary integration.[11] By providing a "view from below", it allows us to identify additional similarities and differences that augment the emerging picture of cross-disciplinary integration.

Integration has been a feature of the research agenda in the philosophy of science for decades, and it has taken many forms. In this literature, domain unification, for example, may be understood as a form of integration (e.g., Oppenheim & Putnam 1958; Mitchell, 2002; but cf. Plutynski, 2013).[12] Moving closer to the day-to-day business of science, talk of integration has blossomed in philosophy of biology. Mitchell's (2002) defense of *integrative pluralism* as a way of thinking about theoretical integration occurs in that context. Other examples include

[10] We follow Huutoniemi (2014), p. 10, in taking a heuristic to be "a fallible method of solving a problem or making a decision" that functions more like a rule of thumb than a hard-and-fast decision rule. See also O'Malley (2013), p. 559, who takes heuristics to be "exploratory conceptual tools."

[11] For a compelling example, see the recent special issue of this journal edited by Ingo Brigandt (Brigandt, 2013).

[12] Domain reduction has often been defended on the basis of inter-theoretic reductions, suggesting a connection between reduction and integration. While we acknowledge this connection, we focus here, largely for reasons of space, on work explicitly addressing integration. See Brigandt and Love (2012) for an excellent summary of views about reduction within philosophy of biology.

integration at the level of the *discipline* (e.g., van der Steen, 1993), and integration across biological *fields*, such as paleontology and evolutionary biology (e.g., Grantham, 2004).

Grantham (2004) shares our interest in getting "clear about what it means to say that some area of science is 'unified'" (p. 134), where he explicitly treats 'unified' as synonymous with 'integrated'. He analyzes integration in terms of the *interconnections between fields*, where fields are conceptual and not "sociological" structures (Darden & Maull, 1977) and interconnections are both theoretical and practical. Theoretical interconnections include explanatory relations, ontological relations, and conceptual relations. Practical interconnections include "development of particular methods to integrate the bodies of data generated by two fields", the use of theories or methods from one field to guide hypothesis development in another, and the use of methods or data from one field to support hypotheses in another (pp. 143-144). Grantham argues that both reductionist and non-reductionist approaches to integration can be explained in terms of interconnection, and that fields can be more or less integrated by being more or less interconnected (p. 140).

In his account, Grantham is not interested in the "global" challenge of mapping out a "grand vision of how all the various sciences are interrelated," but rather the more "local" challenge of developing a notion of integration that "allows us to understand the processes through which neighboring fields become more integrated" (p. 150). Others working on integration in the philosophy of biology share this interest, and some direct their attention even more locally. Focusing on the interdisciplinary field of systems biology, O'Malley and Soyer (2012) provide an overview of integration, distinguishing methods, data, and explanations as three important sites of integration.[13] As they understand it, integration is a "multidimensional activity" that "encompasses the combination of methods and methodologies, … the process of making data sets comparable and re-analysable, and the variety of ways in which explanations are brought together in a particular inquiry" (pp. 59, 66).[14] Within systems biology, integration is sought as a part of a "down-to-earth philosophical view of contemporary biology", one that is "more pragmatic" and concerned more with "a range of connections between fields and research areas" (pp. 66, 62).

Attending to explanatory integration, Brigandt (2010) uses a case study involving the explanation of novel structures in evolutionary developmental biology to argue for a problem-based account. Taking explanatory integration to be "the integration of ideas and explanations from different disciplines so as to yield an overall explanation of a complex phenomenon" (pp. 296-297), he argues that "…solving some complex biological problems … requires at least the partial integration of concepts and explanations from different fields" (p. 304). The focus of this

[13] As an example of *methodological* integration, Swanson et al. (2011) discuss various integrated methods in the context of developing a socially sustainable model of egg production. *Data* integration is the focus of Leonelli (2008), who discusses bio-ontologies as tools for this type of integration. (See also Leonelli, 2013.) *Explanatory* integration is illustrated in Brigandt (2010) below.

[14] Green and Wolkenhauer (2012) provide a similar definition: "Integration might be best described as a combination of activities that provide a more comprehensive and coherent picture of complex research problems, from combining data, models and methodologies, to merging explanations and establishing closer connections among disciplines" (p. 769).

approach highlights the contextual nature of explanatory integration, which can vary in character and degree depending on the integration required by scientists to solve their scientific problem. Brigandt concludes by arguing that so conceived, integration is not a "regulative ideal", or an "a priori condition that is to be achieved in every context," but rather it "depends on the case" (p. 307).[15]

This brief foray into the philosophy of biology reveals significant detail about the structure and function of integration as a process in science, at scales as broad as science itself down to the micro-scale of problem and explanation. There are commonalities among the accounts we have considered. They all take integration to be contextual, although the contexts vary in scale. They also focus on the epistemological side of science, emphasizing the integration of concepts, data, methods, explanations, and theories. But here, as above, there are faultlines. For instance, Grantham (2004) considers integration at the abstract level of scientific fields, while O'Malley and Soyer (2012) and Brigandt (2010) focus more on the concrete circumstances of scientific research down to the level of the specific problem. Second, Grantham (2004) takes integration to be an "important regulative ideal" and so a normative principle that governs how we evaluate scientific explanations; this view is reflected in O'Malley and Soyer's (2012) claim that integration is a "normative requirement" in systems biology (p. 58). By contrast, Brigandt (2010) denies this, arguing that while integration may be important in many cases, its legitimacy and value will depend on the specifics of the case. A third faultline concerns the degree to which the accounts emphasize the *purposiveness* of integration, as Brigandt's does. Integration is purposive when it is practical and sought in combining data, developing a method, or solving a problem. The theoretical integration of fields discussed in Grantham (2004) is less constructed in order to do science than discovered through science, reducing its dependence on the purposive activity of scientists. (See Table 2.)

[Table 2 here]

3. Integrating integration: methodological preliminaries

As stated above, our goal in this paper is to integrate various strands of insight concerning cross-disciplinary integration across two important literatures into a more inclusive framework. While by no means comprehensive, the views described in the previous section illustrate a variety of perspectives on cross-disciplinary integration. This is perhaps not surprising. Given the contextual nature of integration, we would expect an account of integration to be a function of initial conditions. But while some of the differences (e.g., interdisciplinary vs. transdisciplinary integration) could be a matter of emphasis, others (e.g., algorithmic vs. heuristic) correspond to deeper divisions in how people think about integration across disciplines. Still, we assume that the researchers in the previous section are employing the same concept, or in some cases, closely related concepts (e.g., Bammer, 2013).

Of course, one could deny our assumption that these researchers are using the same concept and insist that the best way forward is to interpret 'integration' as having different senses in these

[15] Cf., O'Malley (2013), who discusses integration as a "meta-heuristic" (p. 559).

contexts.[16] Emphasizing differences over similarities would suggest that similarities among theorists are superficial and cannot support substantive agreement about cross-disciplinary integration across contexts. While this would be an important conclusion—and one that would complicate any attempt to plan integrated responses to grand challenges—we believe it is too soon to jump to it. In our view, it is better to start by treating uses of the word in these contexts as univocal, while remaining open to the possibility that it has multiple senses. We seek to shed light on cross-disciplinary integration by considering the many employments of the concept together until close scrutiny demands that we consider them apart.

At this point, it is important to remain mindful of our goal of supplying a framework for cross-disciplinary integration that can help illuminate what is required to address grand challenges. Our strategy will be to get at the sense of 'integrate' operative in cross-disciplinary contexts—the sense relevant to addressing grand challenges—by abstracting away from the different approaches we have considered toward a common framework. We begin by consulting everyday discourse, not because it supplies the sense of 'integration' required to address grand challenges but because it represents a suitably generic starting point for figuring that out and, importantly, nothing in our previous analysis suggests that the theorists we consider take themselves to be breaking with the common understanding of the word.

Following Klein (2012) and Repko (2012), we consult the Oxford English Dictionary for senses of the common English words 'integrate' and 'integration', and we are told that there is an etymological connection between 'integrate' and the Latin word *integrare,* or "to make whole".[17] This root supports several definitions, with one standing out as especially relevant: "2.a. To put or bring together (parts or elements) so as to form one whole; to combine into a whole" ("Integrate, *v*.," n.d.). This sense presents integration as a process, in the *forming of* or *combining into* a whole, and as a product, in the *whole* that is made, a pair of aspects displayed in the accounts of integration considered above.[18] Consistent with those accounts, it also highlights the input (e.g., "parts or elements") and output of integration.

Before proceeding, we need to address the concern that 'integrate' is a technical term in cross-disciplinary contexts, and so consideration of common parlance is a mistake. After all, we would not look to everyday language for guidance concerning use of 'force' in physics, so why look to

[16] See Plutynski (2013) and Brigandt (2013) for two recent articles that adopt this perspective. We suggest that the framework in Section 4 can mitigate their concerns by fitting the diversity of integrative practices into a single, parameterized framework, thus acknowledging the real diversity of integration without sacrificing the insight generated by having an over-arching conceptual framework.

[17] See Klein (2012), p. 284 and Repko (2012), p. 262. For a similar move, see Efstathiou, this issue.

[18] Focusing on making *whole* might seem incompatible with integration in cross-disciplinary research, where integration often produces partial, intermediate combinations that no one would take to be a whole, especially in its early stages. In our view, this turns on a reading of 'whole', understood as the final, complete product, which is not forced on us here. Instead, we can emphasize the process—that is, the *making*—and thereby focus on the creation of connections and removal of incompatibilities that figure importantly into interdisciplinary integration. Cf. Hirsch and Brosius (2014). Thanks to Giovanni De Grandis for conversation about this point.

it for guidance concerning the use of 'integrate' in cross-disciplinary research? Looking back at section two, we find moves consistent with this concern. Bammer (2013) contrasts *integration* with *synthesis*, limiting integration to a more constrained kind of "bringing together". Grantham (2004) uses 'integration' interchangeably with 'unification', which can be understood as combining theories or explanations into a single account. Brigandt (2010) uses 'integration' more generically, to cover both unification and synthesis as types.

These moves could be seen as producing new and incompatible *technical* senses of the term, but there is another way to look at the matter. Following Klein and Repko, we propose that these technical employments are restrictions of a more generic sense of the term, one that we propose is supplied by the OED definition quoted above. Several observations motivate this proposal. First, our understanding of integrative phenomena is still emerging, and so while 'integrate' could well become a technical term akin to 'force' as we develop a stable theory of integration, we are not there yet. Second, researchers investigating cross-disciplinary integration regularly deploy similar metaphors in talking about the process, e.g., *fusing*, *melding*, *blending*, *amalgamating*, *harnessing*, and *knitting*.[19] By subsuming restricted employments of the term under a generic sense, reliance on similar metaphors is explained as the investigators thinking of the same process in slightly different ways. Third, the vernacular definition captures several key features of integration common to the accounts just mentioned as well as the others canvassed in section two, namely, the process/product ambiguity of the term and the input/output structure of the process.

4. Integrating integration: the framework

We propose that integration is a generic combination process the details of which are determined by the specific contexts in which particular instances of integration occur. The contexts we consider involve cross-disciplinary research. In this section we sketch this process along with some general features of its specification in more detail, drawing on the literature surveyed in section two. There are three things to note about our pursuit of this goal. First, although we do not consider contexts outside of cross-disciplinary research, this approach suggests that there will be important commonalities with integration in other domains. Second, we do not aim to provide a normative model of what integration *should* be, but rather produce a description of what it *is* in view of important contributions to literatures on cross-disciplinary integration. Finally, this approach to integration gives us resources to use in integrating discussions of cross-disciplinary integration, thereby highlighting features of cross-disciplinary integration that will figure prominently in responses to grand challenges.

Grand challenges are *wicked* challenges whose character can change in unpredictable ways (Rittel & Webber, 1973); given this, remaining nimble in response will be critical to success. While the product of integration is clearly important, at least when it comes to grand challenges,

[19] As Boix Mansilla (2010) observes, "a striking array of metaphors have been deployed to describe the nature of interdisciplinary intellectual activities" (p. 289). While her observation is not limited to integration, her point that these metaphors serve as "evocative approximations of interdisciplinary cognition" is germane. While there are differences among the metaphors we list, one striking aspect of them is that they are all approximations of a process in which different things are combined into one.

attention to process must come first and remain a constant part of the response. We thus foreground the *process* of integration, subordinating its *product* character by taking the product to be the result of the process.[20] We treat integration as an input/output process, where a series of changes to the inputs results in a "bringing together" or combination of inputs, producing an output. The theorists agree that aspects of integration vary with context, from inputs to outputs. Not all of them address how the process varies, though. We pursue the idea, reflected in talk of "dimensions" in O'Malley and Soyer (2008, p. 65) and Bergmann et al. (2012, p. 44), that the specific sense of 'integration' in context is determined by setting various parameters. In what follows, we detail how the generic sense of 'integration' given above can be developed to get a picture of cross-disciplinary integration as a parameterized input/output process.

4.1 Inputs and outputs

We begin with inputs and outputs. Inputs are combined in the process and the output is the "whole" produced. Both vary by context, as the examples we have considered illustrate; as such, a full list of inputs and outputs is impossible. We can, however, address certain kinds of inputs/outputs and some useful ways to think about them.

All theorists make room for a cognitive dimension to integration, so cognitive elements may appear as both inputs and outputs. More specifically, both local *epistemic* elements—e.g., concepts, methods, data, explanations, knowledge, and models (cf. Brister, this issue)—and global epistemic achievements—e.g., theories, fields, disciplines, and even whole domains—may serve as inputs and outputs.[21] Some theorists (e.g., Klein, Bergmann et al.) go beyond the epistemic in the direction of the communicative and social, considering integration that involves languages, social problems, project participants, and supporting institutions.[22] Others go in a more ontological direction—Repko (2012), for example, allows that concrete objects such as photographs or film could be integrated, although for him these would need to involve disciplinary insights (p. 281).

When organizing one's thinking about inputs/outputs, it helps to think of them along two dimensions, quality and quantity:

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[20] In this we follow Bergmann et al. (2012), p. 43, Repko (2012), p. 262, and Klein (2012), p. 288. This approach is also reflected in the structure of Bammer's (2013) "five-question framework" (p. 20); cf., Pohl et al. (2008), p. 422 and Brigandt (2013), p. 463. All of our theorists take integration to be a process, even those such as Grantham (2004) who speak of field unification. As we noted above, one could take the integration of fields to be *discovered* by attending, for example, to relationships among their ontologies; however, fields are epistemic objects developed over time, and their discovered integration will have emerged during that development through a non-purposive process, if it was not itself purposive.

[21] Fields, disciplines, and domains also have essential social dimensions, which are subordinated by theorists like Repko and Grantham to their epistemic dimensions.

[22] Key aspects of the latter two elements include work ethos and values; see Leonelli's (2013) discussion of "translational" integration for relevant examples. Also, values and institutions are central to the notion of "practical" integration—see De Grandis, this issue.

- Quality: What is the character of the inputs/outputs? (Are they cognitive? Epistemic? Social? Are they abstract or concrete?) How do inputs into a process differ? How do outputs differ?

- Quantity: How many different kinds of inputs/outputs are there (e.g., inputs/outputs at different levels of organization, as in Brigandt, 2010)? How many inputs/outputs of a particular kind (e.g., data sets, disciplines) are involved? (The quantity of inputs is associated with the *scope* of the integration process under consideration.[23])

While these may not be the only dimensions along which inputs and outputs vary, they capture important attributes that distinguish episodes of integration across cross-disciplinary contexts.

4.2 The integration process

Since integration is a type of putting or bringing together of inputs to produce a whole, there is an important precondition for integration: inputs must be capable of being integrated, i.e., they must be "connectible" (Bergmann et al., 2012, p. 28). If inputs cannot be integrated, the process will not initiate and the inputs will not change. As we discuss below, though, two inputs can be integrable even though they conflict; indeed, overcoming disciplinary conflict is regarded by some theorists (e.g., Newell, Repko) as a central characteristic of cross-disciplinary integration.

If the inputs are integrable, combinational changes can commence. Many of these changes are described by our authors. At a general level, Grantham (2004) distinguishes broad types of integrative change (viz., theoretical and practical), while Newell (2007) and Repko (2012) discuss techniques for effecting various changes to inputs (viz., redefinition, extension, organization, and transformation). More specifically, O'Malley and Soyer (2012) describe a number of integrative changes, such as sequencing of evidence, with "one line of evidence … used to back up a hypothesis already supported by another line of evidence" (p. 59). Integration of theories, explanations, and other epistemic inputs is also described in terms of *levels* (Klein, 2012): two theories (say) about the same phenomena might be integrated if they are understood to operate on different explanatory levels (O'Malley & Soyer, 2012), or integration might require something more, such as interlevel connections (Grantham, 2004), which, in our view, may be reductionist (Oppenheim & Putnam, 1958) or non-reductionist (Brigandt, 2010). Another specific example of integrative change concerns communicative integration within interdisciplinary contexts, which can be effected by disambiguation and joint definition (Bergmann et al., 2012), translation, or even the joint creation of a new "interlanguage" (Klein,

[23] The example of scope highlights a duality in our notion of quantity. Discussions of scope require consideration of both the number of input perspectives and the degree of difference between those perspectives (as opposed to the nature of the difference, a quality consideration). While the number can be captured with a discrete numerical quantity, degrees of difference are typically understood using a spatial framework—two perspectives might be near or far apart in the space of concepts. Spaces are typically thought of as having continuous rather than discrete metrics and we often use loose comparative terms (e.g., 'near', 'far') rather than precise measurements when discussing them.

2012).[24]

As above, thinking about these changes in terms of their quality and quantity helps facilitate comparison. On the quality side, we note three aspects characteristic of the combinatorial changes that count as cross-disciplinary integrations. First, they are combinational – they "put or bring together" the inputs.[25] The integration process, then, takes inputs that are not integrated and puts or brings them together into an *integrative relation.*[26] The metaphors mentioned above express integrative relations: *fusing*, *melding*, *amalgamating*, *knitting*, and the rest. Our authors also discuss others: "linkage" of disciplinary knowledge (Newell 2007, p. 260; Bergmann et al. 2012, p. 44),"making sense together" as a means of creating mutual understanding (Klein, 2012, 295), "interconnection" (Grantham, 2004), and "harnessing" differences (Bammer, 2013). These are contrasted with disintegrative relations, such as disassociation (Brigandt, 2010), differentiation (Bergmann et al., 2012), and boundary setting (Bammer, 2013).[27] In between there are combinational relations that are disputable, e.g., *assembling*, as one might a puzzle. Some, like Bergmann et al. (2012, p. 45) see puzzle assembly as a type of integration; others, however, are disinclined to see it as integration because puzzle pieces go together without difficulty and (in some cases) by design. Our proposal is capable of accommodating such cases, or their cross-disciplinary analogues.[28] What matters here is that, in general, integration in the cross-disciplinary context involves bringing inputs—whether they be cognitive, communicative, or social—into an integrative relation, i.e., into a combination that supports interpretation of them as a single, coherent whole.[29]

Second, most of the authors emphasize the *purposive* character of cross-disciplinary integration. Our characterization of cross-disciplinary integration as a parameterized input/output process does not require it, though, and there will be dimensions of cross-disciplinary integration that are best understood as emergent and not purposive. Not all "bringing together", even when it involves people, is purposive as such.[30] What seems like purpose might emerge out of the actions of people that are aimed at different specific goals (e.g., the research priorities of large academic department). Nevertheless, an important aspect of the process is that it can be goal-directed, pushed forward by people who function as integrators of language, knowledge, and teams.

A third qualitative aspect concerns the way the process can unfold. As we have noted, some take integration to comprise algorithmic changes (e.g., Newell, 2007; Bergmann et al., 2012; Repko, 2012) while others see it as involving more constructivist, heuristic changes (e.g., Klein, 2012;

[24] Cf. Holbrook's (2013), pp. 1874–1876, discussion of the Bataille-Lyotard thesis and "strong communication".

[25] This is true even in cases of high change (see below) where no trace of the inputs remains.

[26] See Brigandt (2010), pp. 305–308, for relevant discussion.

[27] See O'Malley (2013) for relevant discussion of a failure of integration.

[28] We are grateful to a referee for pushing us on this point.

[29] We regard this as the first step in the direction of a deeper analysis of these relations. Additional work is required to identify different integrative relations, determine if there is an independent way to account for their integrative character, and specify what counts as successful integration in a particular case. Cf. Bennett (2011) for a related discussion of a similar problem regarding "building" relations.

[30] Thanks to an anonymous referee for emphasizing this point.

Bammer, 2013). In general, the former group will take integration to be less variable than the latter, although both can allow for variation across contexts.

When thinking about quantitative aspects of the integration process, it can helpful to track the number of specific changes required to produce the output, as well as the number of kinds of change. One can also take 'change' to be a mass noun and ask whether the process leaves the inputs alone but simply connects them (low change), transforms them into something wholly new (high change), or perhaps something in between where the inputs remain but are reconceived collectively.[31] In this sense, the quantity of change amounts to how *complete* the change is, i.e., how thoroughly does the process integrate the inputs? Do they retain their character in the output, perhaps ordered sequentially such as methods that feed one into the other (O'Malley & Soyer, 2012), or is their character fully transformed in the process of integration (Repko, 2012)?

4.3 Integration parameters

Understanding integration as an input/output process allows us to accommodate variations in accounts of integration across different cross-disciplinary contexts. Integration differs on these accounts in terms of the quality and quantity of inputs, outputs, and the types and intensity of integrative change leading from one to the other. Additional variation is induced into the framework via parameters that cut across the categories we have considered and can be adjusted from context to context. A number of these parameters emerged in section two, and we profile three of the most prominent.

- *Scale* (Global/Local): What is the scale of cross-disciplinary integration? Does integration operate globally (e.g., the domain level, such as all of biology), locally (e.g., data sets, specific problems), or somewhere in between (e.g., disciplines, fields)? This will influence the nature of inputs, process, and outputs.

- *Commensurability* (High conflict/Low conflict): Are the inputs integrable, or must conflict be reduced before they can be combined (Newell, 2007; Repko, 2012)? Does the integration process leverage conflicting differences while transcending them (Klein, 2014)? Can integration take place if conflict is minimized (Bergmann et al., 2012, p. 45)? This parameter will affect inputs and process.

- *Comprehensiveness* (High/Low): How comprehensive will the output be, relative to the inputs? For example, will the integration process result in a cross-disciplinary output that provides a more comprehensive view of a problem than the disciplinary inputs (Newell, 2007, Boix Mansilla, 2010), or will it result in an innovative but focused cross-disciplinary output that is a "vector sum" of the inputs without being more comprehensive (Bergmann et al., 2012)? This will influence inputs, process, and outputs.

Our proposal, then, is that cross-disciplinary integration is a parameterizable input-output process that yields different types of integration in different contexts. (See Fig. 1.) All of the accounts of integration discussed in Section 2 can be accommodated in this framework. Consider

[31] Once again our notion of quantity has both discrete and continuous aspects. See note 24 above.

Repko (2012): by defining 'interdisciplinary integration' as "the cognitive process of critically evaluating disciplinary insights and creating common ground among them to construct a more comprehensive understanding" (p. 263), he commits to a view of integration where the inputs and outputs are cognitive and the process is high conflict, high comprehensiveness, mid-scale, and involves bringing inputs into the "common ground" relation via steps that are purposive and algorithmic. What Bammer (2013) calls "integration" and "synthesis" qualify as two specific instances of integration according to our framework, differentiated by the nature of the inputs and the outputs. Since many of the accounts discuss integration in multiple contexts, the specific nature of the process will vary for them—this is true, for example, in Grantham (2004), O'Malley and Soyer (2012), and Bergmann et al. (2012). While there is clearly more work to be done to develop this framework, its suitability as a frame for the accounts considered in Section 2 supports the idea that *integration* is a generic concept that only appears polysemous due to the fact that it can be specified differently in different contexts.

[Figure 1 here]

5. Conclusion

Is there anything useful to be said, in a generic way, about cross-disciplinary integration? A number of attempts have been made to identify critical features of integration that apply to cross-disciplinary research, including those based on general theoretical considerations (Section 2.1) and others based on salient features of particular cases (Section 2.2). In our view, while all the approaches we consider have merit, none of them captures the full range of features that figure into cross-disciplinary integration. The framework we supply in Section 4 comprises a more adequate set of features, although exploration of additional accounts in these literatures as well as in others (e.g., communication theory) is required to be confident of the framework's elements.

As a broad way of thinking about cross-disciplinary integration, however, this framework can perform a service to those working on grand challenges such as those in the biological and biomedical sciences described in the introduction. As we noted above, successful responses to grand challenges will require cross-disciplinary integration, but constructive combination of different perspectives can be undermined if collaborators conceive of integration differently (O'Rourke & Crowley, 2013). As we have demonstrated with the accounts presented in Section 2, this framework can be used to highlight differences and similarities among different views, thereby calibrating those views and setting the stage for more productive negotiation and compromise.

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Tables and Figure

View of Integration	Focal Context	Nature of Integration	Key Features
Newell (2001, 2007), Repko (2007, 2012)	Interdisciplinary research	• Contextual, purposive: create common ground with integrative techniques in specific contexts • Algorithmic, iterative • Cognitive, individual • Produces a more comprehensive understanding of a problem out of disciplinary concepts and assumptions where the whole is greater than the sum of the parts	Integration: • decreases conflict • involves complexity • occurs late in the interdisciplinary process • admits of degrees
Klein (2012)	Cross-disciplinary research	• Contextual, purposive: generate mutual understanding via communicative rationality in specific situations • Heuristic, iterative • Considers cognitive and social elements, collaborative and individual processes • Full range of cognitive and social elements (e.g., knowledge, goals, methods; participants, institutions, disciplines) combined in pursuit of "making sense together"	Integration: • does not adhere to a universal formula • can be enhanced by "platforming" • can be achieved via language, concepts, models, methods, or frameworks
Bergmann et al. (2012)	Transdisciplinary research	• Contextual, purposive • Algorithmic, recursive • Collaborative • Has 3 dimensions (communicative, social, and cognitive) and several content-relative types • Real societal problems and disciplinary perspectives combined in pursuit of results for social and scientific practice	Integration: • requires reconciliation of elements and critical monitoring of results • must be the focus from beginning of process
Bammer (2013)	Complex, real-world problems requiring research and policy responses	• Contextual, purposive: pursue practical responses to real world problems in context • Heuristic, iterative • Primarily cognitive and collaborative • Combines synthesized disciplinary and stakeholder knowledge with considered response to unknowns	Integration: • can be planned • is distinguished from *synthesis* • concerns responding to unknowns

Table 1. Survey of views on integration in the cross-disciplinary literature

View of Integration	**Focal Context**	**Nature of Integration**	**Key Features**
Grantham (2004)	Biological fields, e.g., paleontology and evolutionary biology	• Involves theoretical or practical interconnections among fields • Focuses on field-level episodes of integration • Reductive or non-reductive • Data, methods, and concepts at the field level are interconnected theoretically or practically	Integration: • is synonymous with unification • varies by degrees • is a regulative ideal
O'Malley & Soyer (2012)	Systems biology	• Focuses on local, practical episodes of methodological, data, and explanatory integration • Mechanisms of integration include exploratory questioning, technological innovation, and transfer of tools, methods, and explanations • Involves method combination, data sets made comparable and re-analyzable, explanations brought together	Integration: • is multidimensional • presupposes significant difference • is a practical and normative requirement in systems biology • is a foundation for a "more developed account of scientific practice" (66)
Brigandt (2010)	Evolutionary developmental biology	• Focus on explanatory integration • Contextual, purposive • Operates at scientific problem scale • Involves ideas, explanations, models, etc. linked in solving a scientific problem	Integration: • can be stable but need not be • is not a regulative ideal • comes in degrees

Table 2. Survey of views on integration in the philosophy of biology literature

1

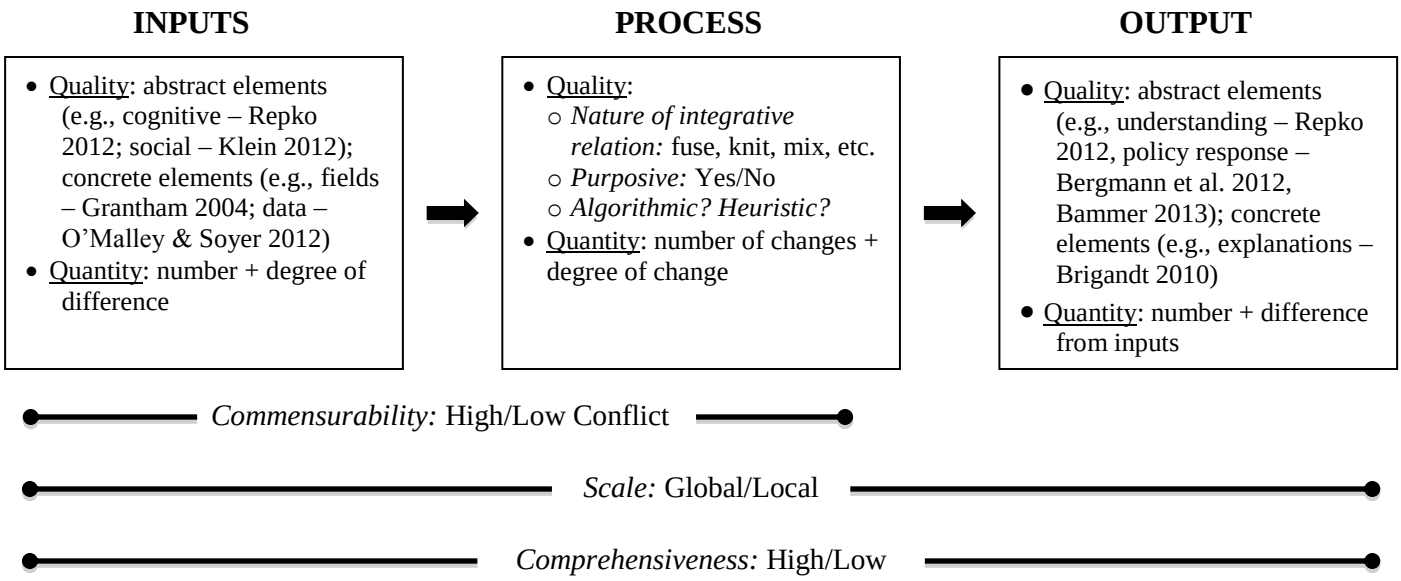

Fig. 1. Schematic diagram of integration as an input/output process parameterizable in terms of cross-cutting dimensions that induce variation into the integrative process.