Multidisciplinary Research as a Complex System

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Abstract
Collaborative research has become increasingly prominent since the mid-20th century. This article aspires to offer a fundamental ontology of a multidisciplinary research system. As a point of departure, we consider disciplinarity as a restricted language code as noted by Bernstein. The impetus for collaboration is found in a research problem’s transcendence of disciplinary bounds. This article makes several propositions that diverge from the consensus position regarding the formation and dynamics of a multidisciplinary system. Most notably that such a system adheres to the constituent elements of what could be regarded as a complex system, including an ensemble of elements, interactions between these elements, local disorder followed by the emergence of robust order and system memory. We propose that the internal communications and subsequent self-organization of such a system may be conceptualized as orientation signals, or ‘stigmergy’, analogous to those observed in swarms. System robustness, we argue, is a function of the individual researcher’s local autonomy and is, paradoxically, augmented by the weakness of communications across disciplinary bounds, along with the lack of central organization and the emphasis on research novelty. System memory, we argue, manifests itself in the ability of a researcher to change her/his route of inquiry, based on environmental feedback, whereby new information becomes incorporated into the adjusted research methodology. We propose that an emergent intelligence, at the level of the system, expresses itself in the unconcealment of the ‘form’ of the metaproblem. The theoretical model is empirically illustrated using, as an example, the contemporary field of renewable energy research, which is an area primed for collaborative research. It is anticipated that an improved understanding of multidisciplinary research systems provides insights into certain strengths particular to less integrated and self-organized forms of collaborative research along with a framework with which to improve the design and fostering of such systems.

Keywords
mixed methods, secondary data analysis, qualitative evaluation, philosophy of science, case study

Introduction to Collaborative Research

The Problem of Terminology
Since the middle of the 20th century, a shift away from monodisciplinary research has been observed, towards forms of collaborative research (Baldwin & Austin, 1995; Sanderson, 1996). One reason for this transition is the result of both increased specialization and dynamic growth of knowledge within the fields of academic inquiry, concurrent with the increased scale and complexity of the problems that researchers are tackling (Hara et al., 2003). As a result, there has been an increased interest in understanding collaborative research systems. Certain authors make insightful arguments for distinctions between collaboration, cooperation (Hord, 1986) and coordination (Castañer & Oliveira, 2020). However, as argued by Gulati et al. (2012) and Salvato et al. (2014), we use collaboration, derived from the Latin cum laborare, as an umbrella term simply meaning working together, which is intended to incorporate the more nuanced cooperation and coordination.

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Literature on collaborative research is extensive, ranging in purpose from enabling scientific communities to ‘realize epistemic goals’ (Wray, 2012) to the elucidation of conditions that either promote collaboration, such as technology, place, methods and data accessibility (Hunter & Leahey, 2017) or hinder collaboration – different practices, beliefs and goals (Hara et al., 2003). Indeed, difficulties associated with successful disciplinary collaboration and integration have been noted by several authors (e.g. Balsiger, 2004; Petts et al., 2008; Stevens et al., 2007). Various reasons for failures in collaborative research have been proposed including epistemic and ontological incompatibilities (Petts et al., 2008), a level of superficiality that may be inherent to collaborative research (Massey et al., 2006), interpersonal and/or political problems (Kaufmann et al., 2020) and barriers related to the use language and terminology between disciplines (Stock & Burton, 2011).

Adjacent to the problem of language and terminology amongst disciplines is the problem of how forms or types of collaborative research are defined, understood and ultimately structured. Various naming conventions and associated definitions on collaborative practices have emerged and some authors have argued that the categories of collaborative research are not (as yet) clearly defined enough to illuminate or even guide empirical research on the nature and function of forms of collaboration (Claveau & Fernández, 2015). A few examples of such ambiguities include ‘polidisciplinarity’ found in medical practice (Alvargonzález, 2011) or hybrid disciplinarity in bio-engineering (Nersessian, 2019), ‘fuzzy’, distributed, corporate collaborations designed to foster innovation (Takahashi et al., 2018), and ‘supradisciplinary’. Ambiguities regarding the naming conventions, definitions and descriptions of collaborative research notwithstanding, an emerging body of literature seems to be triangulating on three categories to be used that describe collaborative research: multidisciplinary, interdisciplinary and transdisciplinary. Examples of studies making use of the multi-inter-transdisciplinary categorization, to name a few, include Alvargonzález (2011), Choi & Pak (2006), Collin (2009), Fawcett (2013), Klein (2008), Stock & Burton (2011), Uwizeyimana & Basheka (2017).

A renowned problem in structured collaborative research projects is the oft-cited failures of disciplinary integration, despite working towards a communal goal (Bruce et al., 2004; Stevens et al., 2007; Tress et al., 2007). This article sets out to develop a fundamental ontology of a multidisciplinary research system, drawing strongly from complexity theory. In doing so, the aim of this article is twofold: firstly, to encourage a paradigm shift away from a classic top-down approach to structuring collaborative research projects by elucidating certain strengths particular to a less-integrated and self-organized approach to collaborative research. As multidisciplinary research is often considered to be the first within a collaborative research hierarchy, or the least integrated of the research systems, we deem multidisciplinary research to be a good point of departure when introducing complex systems thinking into the study of collaborative research systems.

Secondly, it is anticipated that augmenting our understanding of collaborative research with complex systems theory would provide key role players with a new framework with which to improve the design and fostering of such systems and enable the continued optimization of collaborative research. Renewable energy research is used as an example throughout the article, as an area primed for collaborative research due to the societal scale and complexity of the being investigated.

**Scientific Disciplinarity**

A scientific discipline, as a measure of internal differentiation, is fundamentally understood by the authors in terms of Bernstein’s linguistics (Bernstein, 2003) as a restricted language code. In essence, the ‘speakers’ converse in an internal and fairly homogeneous ‘repertoire’ of discourses and practices which might not be shared beyond the borders of the discipline. To this effect, Stock & Burton (2011) note that working within a defined discipline may provide researchers a measure of ontological and epistemological certainty that may be necessary for scientific progress. In a prominent essay by Stichweh (2008), it is argued that specialized scientific disciplines emerged at the end of the 18th century as a result of the culmination of a number of preceding events. The most notable of these events were as follows: the structural differentiation from the older established fields of study, such as theology, medicine and philosophy; the development of certain occupational roles as demanded by societal and economic forces and the establishment of disciplines as educational fields in colleges and universities.

Disciplines such as the natural sciences are termed hierarchical knowledge structures, which manifest as ‘general propositions which integrate knowledge at lower levels’ (Bernstein 2000, p. 172). Such knowledge structures see a cumulative progression over long periods of time, with the development of discourses unique to the particular discipline. Horizontal knowledge structures, on the other hand, such as mathematics or economics, are those which are segmentally structured (Bernstein, 2000) through the addition of ‘languages’. In other words, there are different types of mathematics and economics ‘languages’, each with their own rules, and which are acquired through addition rather than the subsumptive accumulation observed in hierarchical knowledge structures. Professional fields, such as medicine and engineering, are constituted through a ‘regionalization’ of hierarchical and horizontal knowledge structures, often blurring the original disciplinary boundaries. Therefore, a discipline may be summarized as a strong structural classification of a specific knowledge area with a defined epistemological foundation which provides it with an internal autonomy and economy of communication with rules of access to outsiders.

**Collaborative Research**

A useful point of departure in multi-, inter- and transdisciplinary research, as suggested by Alvargonzález (2011), is in
considering the definitions of the prefixes multi-, inter- and trans-. The English prefix multi, from the Latin multus, indicates ‘that something consists of many things of a particular kind’ (Harper Collins Publishers Limited, 2020). Multidisciplinary, therefore, refers to an activity consisting of many disciplines. Though exact definitions differ marginally between articles, multidisciplinary research is often considered to be the basis, or perhaps the first step, in the establishment of a collaborative research system. Its key feature is typically understood as the ‘non-cooperative’ aspect of the interaction between researchers as formulated, perhaps most influentially, by Jantsch (1972). The structure of a multidisciplinary system could therefore be regarded as a ‘collection code’ (Bernstein, 1975), as opposed to an ‘integrated code’ which requires lateral cooperation through relatively porous disciplinary boundaries.

The Latin prefix inter, means ‘between’ and ‘among’, ‘connects two or more places, things, or groups of people’ (Harper Collins Publishers Limited, 2020). An interdisciplinary activity therefore means an activity that connects two or more disciplines. Thereby, the key feature of interdisciplinary research is the emphasis on the cooperative aspect where researchers from different disciplines work communally with a larger degree of centralized control on a predefined problem, thus actively facilitating the integration of multiple perspectives into a research outcome. The key difference between the meanings of these prefixes is that inter- signifies reciprocity and multi- does not.

Finally, the Latin prefix trans, means ‘on the other side of’, or to, is used to indicate that ‘someone or something moves from one group, thing, state, or place to another’ (Harper Collins Publishers Limited, 2020). Collaborative research systems designated as being ‘transdisciplinary’ are often described as adopting a holistic approach (transcending disciplinarity and the line between science and practice, for example, Jerneck et al. (2011)) through the inclusion of inputs from outside of a research system, such as industry, governmental and community stakeholders.

**Article Overview**

The rest of the article progresses as follows: The Multidisciplinary Research: Emergent Complexity section provides the fundamental ontology of a multidisciplinary research system; the Multidisciplinary Approaches to Renewable Energy Research section provides an example of the emergence of a multidisciplinary research system within the context of renewable energy research and the Conclusion section concludes the article. The novel contribution made by this article is in conceptualizing multidisciplinary research from the perspective of complex systems. This article furthermore introduces a useful vocabulary in terms of which collaborative research may be considered and may open further avenues of investigation. From a practical perspective, it is deemed that this article may assist researchers and research-institutions in structuring their collaborative research efforts. This article is the first in a series of three dealing with collaborative research systems. The second article deals with interdisciplinary research systems and the third takes a holistic approach to collaborative research considering the interactions between collaborative research systems.

**Multidisciplinary Research: Emergent Complexity**

**The Researcher-Problem Dyad**

The model of a multidisciplinary research system as presented in this article, though novel in its vocabulary and dynamics, is at its inception aligned with the traditional view as postulated by Jantsch (1972) which considers research as a teleological process. This view considers the teleology of research (collaborative or otherwise) as a process aimed at resolving the dyadic tension between a manifest problem and a researcher, assuming axiomatically (and admittedly somewhat coarsely) that researchers investigate and solve problems. However, as highlighted by Klein (2008), the shape of a given problem does not necessarily correspond to the boundaries of a discipline – particularly when considering increasing specialization of various disciplines.

This article introduces the term metaproblem to refer to problems that transcend disciplinary bounds, thereby becoming the subject of collaborative research efforts. For example, within the burgeoning field of renewable energy research, the energy transition may be considered as a social-ecological complex system (Westley et al., 2013) on a societal scale that invokes an ecosystem of interconnected subproblems and processes, the sum of which supersedes the routes of inquiry that any single researcher or monodisciplinary team is wont to take. Problems encountered in such complex systems are auspicious examples of where conflicting social, environmental and economic needs may be encountered (Vanasupa et al., 2014). The metaproblem refers to this ecosystem of interconnected subproblems and processes.

The initial impetus towards collaborative research lies in the metaproblem’s transcendence of individual disciplines, which renders the discipline-specific researcher’s conceptualization thereof essentially untenable. This echoes the sentiment of the world and its problems having become ‘too big to know’ as discussed by Weinberger (2011). An individual researcher perceives a subsection of the metaproblem, along with various subproblems and processes, through a personal lens, or disciplinary ‘gaze’, whereby the clarity with which these subproblems, processes and their interrelations are understood is a function of disciplinary constraints. Due to increased contemporary specialization of academic research, it may be argued that a researcher’s disciplinary gaze, and his/her associated understanding of the metaproblem, is potentially increasingly limited. The issue of hyper-specialization
and its possible pitfalls such as disciplinary blindness and compartmentalization of knowledge has been noted by various authors both from within the academic establishment (e.g. Bernstein, 2015) and within popular media (e.g. Taylor, 2009).

We consider an individual researcher’s conceptualization of the metaproblem as a vague superstructure embedded with specific points of greater clarity corresponding to the researcher’s areas of specialized knowledge. For example, an electrical engineer’s understanding of a metaproblem such as the energy transition towards renewable energy might be very ‘clear’ in terms of the technical challenges associated with installing variable renewable energy onto a power grid, but very ‘vague’ in terms of other sub-problems within the metaproblem superstructure such as the politics behind formulating an acceptable energy policy, the economics of the energy transition and the mitigation of climate change. It thus follows that researchers in their respective disciplines define their research aims and methodologies – their particular ‘grammars of inquiry’ (Morrow, 2015) – based on these conceptualizations and focused on a sub-problem within the metaproblem and proceed accordingly.

For an example of these different grammars of inquiry in approaching subsets of the same metaproblem of the energy transition, consider the following: an electrical engineer may set out to define and subsequently falsify a hypothesis about the impact of wind power variability on an electricity network (e.g. Fertig et al., 2012); a mathematician or economist may, working from a set of axioms and assumptions, set out to deduce (or calculate) the financial costs of installing variable wind power onto a network (e.g. Hirth, 2020); an environmentalist may assess the impacts of wind power on the environment (e.g. Wang & Wang, 2020) and a moral philosopher may set out to argue, likely based on a pre-established hierarchy of values, why or (why not) such a transition may (or may not) be necessary (e.g. Milchram et al., 2019).

A Complex System?

Consider a number of researchers from multiple disciplinary domains and working with a large degree of local autonomy (as may be anticipated, for example, in faculty or tenured positions at universities), investigating different sub-problems within the same metaproblem. These researchers, despite perhaps being separated by departments, institutions, countries and (most importantly) their disciplinary grammars of inquiry, are nevertheless broadly unified in the purpose of their research – in their perceptive orientation towards their object of inquiry. This unity of purpose amongst researchers serves as the inception point of the multidisciplinary research system.

We make the case that such an array of researchers conforms to various conditions of what may be termed a ‘complex system’. Though the literature on complex systems is vast, the frequently cited review article by Ladyman & Lambert (2013) provides a succinct summary of a number of elements considered common across complex systems, which are used to guide our ontology of a multidisciplinary research system. According to Ladyman & Lambert (2013), these conditions may be summarized as follows: ‘an ensemble of many elements’ (as already discussed); ‘interactions’; ‘disorder’ and ‘robust order’ and ‘memory’.

**Disorder, Interactions and Self-organization**

Let us consider the interactions and proliferation of information between elements within a multidisciplinary research system, which we argue allow for the emergence of robust order from local disorder. Ladyman & Lambert (2013) consider robust order as the patterns that emerge and are maintained at a macroscopic level from system elements interacting at the local level in a seemingly disordered fashion. Due to the high degree of local autonomy – and local disorder – of the various researchers, and the lacking central organization, we propose adopting the (at first seemingly radical) swarm intelligence allegory in describing the dynamics of communication within the system which facilitates the emergence of robust order. Swarm Intelligence is a social insect metaphor that refers to an emergent competency arising from multiple, relatively simple, self-organized agents engaged in an activity (Bonabeau et al., 1999; Heylighen, 2016). The metaphor has found a wealth of practical applications and has been studied both quantitatively and qualitatively within many disciplines including logistics (Zhang et al., 2015), optimization (Abraham et al., 2006), robotics and communication (Bonabeau et al., 1999).

Coordination and self-organization within swarms are facilitated through traces left in the environment known as stigmergy (Heylighen, 2016). A classic example of stigmergy is the pheromone trails left by foraging ants en route to a food source. If food is found, the pheromone trail would be enforced as the ant would follow the same trail back similarly leaving pheromones en route (Sumpter & Beekman, 2003). Other ants would detect and follow these trails to a viable food source further reinforcing them. Accordingly, a feedback loop is created between agents within a system. Thereby, stigmergy is a form of indirect communication between agents that facilitates coordination ultimately leading to self-organization, which enables the emergence of swarm intelligence (Heylighen, 2016).

Due to the high degree of local autonomy in a multidisciplinary system, it is proposed that a useful way of thinking about communication within the system is as fairly indirect orientation signals – or stigmergy – used to inform local ‘course adjustments’ with regard to the investigations of researchers. Stigmergy within a multidisciplinary system may arise from various sources both internal and external to the system. Internal sources of stigmergy include the information directly generated during the process of inquiry – that is, from the interaction between researchers and the metaproblem – such as results, findings and methodologies and publications from other researchers and disciplines exploring the same set of sub-problems or related issues within the metaproblem.
When considering interactions of a multidisciplinary research system with the ‘outside world’, our conceptualization departs from the consensus position, which emphasizes researchers essentially being confined to their disciplinary silos. Indeed, we consider the disciplinary silo allegory – that is, rift between academia and the ‘real world’ – to be fundamentally invalid. In a real world analysis, it is deemed that no research takes place in a bubble (frequent analogies to the ‘citadel’ or the ‘ivory tower’ of academia (Rose, 2019) notwithstanding) and that researchers – by the very nature of living in the world – are influenced by factors from outside of the system and indeed also exert their influence to outside the system. Our argument here is, however, in keeping with an understanding of the boundaries of complex systems. Let us consider Cilliers’s (2001) position that a complex system is essentially an open system where the boundary of the system is not something that separates it from the environment, but rather something that connects the system to the environment. To describe the interaction of a multidisciplinary system with its environment, we borrow nomenclature from the field of economics whereby influences from outside the system impacting an individual researcher are termed externalities and influences that the system has on its environment are termed internalities. A few simple examples of notable externalities that may influence a researcher’s orientation include funding opportunities and industry collaboration (e.g. Goldfarb, 2008; Gulbrandsen & Smeby, 2005), institutional objectives (e.g. Prasad et al., 2019), political and social pressures (e.g. Tian & Lu, 2017; Young et al., 2017) and ethical considerations (e.g. Greville et al., 2019). Thereby encapsulated of our understanding of externalities is the proposition that the individual elements of this complex system – that is, the researchers – are extremely sensitive to their environmental conditions, which is in keeping with complex systems literature. Such sensitivity to environmental conditions is substantial in formulating a personal and organizational route to a food source is discovered (in keeping with the swarm metaphor) would reposition the research process, based on route adjustments informed by feedback, the route inquiry is optimized – that is, a shorter path to a food source is discovered (in keeping with the swarm metaphor) – and system memory is both maintained and updated.

**Adaptive System Memory**

Next, let us consider memory within a multidisciplinary research system. Ladyman & Lambert (2013) considers complex system memory as the persistence of internal structures and thereby an outcome or corollary of robust order. Though we agree with Ladyman & Lambert’s (2013) view that a complex system’s memory lies in the maintenance of certain internal structures, we feel that this view does not adequately incorporate the teleological aspect of the research process, which we understand as being key to maintaining system memory and structure. Therefore, we propose considering a multidisciplinary research system in terms of what Perlman (2004), in his taxonomy of teleology, describes as a Naturalistic, Reductionist and ‘Looking to the Recent Past’ system. Such systems, according to Perlman (2004), are essentially focused on goals (which are founded in the fairly recent past) and towards their fulfillment. A key feature of such systems is their ability to adjust behaviour and in so doing circumvent problems that may arise. Indeed, the ability to change course (i.e. the research aim) or approach (i.e. research methodology) is naturally an inherent feature of the research process. We call such adjustments in aims and methodology the dynamic route of inquiry, which is essentially informed by system stigmergy, specifically by the outcomes of previous inquiries (by the same or other researchers) with a similar research aim, the results of which are likely published. For example, should a article be published which points out a flaw in a methodology being pursued by a researcher, or should a researcher discover this flaw in the methodology him/herself, then this methodology would be altered appropriately, and the alteration would reflect the incorporation of the new information. According to Nissen (1997), who is a proponent of what Perlman (2004) considered the ‘Looking to the Recent Past’ teleology, such feedbacks necessarily form a goal-orientated system. Consequently, based on route adjustments informed by feedback, the route inquiry is optimized – that is, a shorter path to a food source is discovered (in keeping with the swarm metaphor) – and system memory is both maintained and updated.

**Robustness**

Finally, let us consider what makes such a system robust. Robustness as noted by Ladyman & Lambert (2013) is linked to local organization, which the authors interpret as being based on the autonomy of the individual researcher. In a multidisciplinary research system, we contend that individual researchers remain semi-autonomously engaged in fulfillment of the research process, based on their perceptions of the metaproblem, and their chosen route of inquiry. The autonomy of the individual researcher is firstly fostered by the lack of centralized organization, which protects the system from the introduction of a centralized directive, as may be seen in an interdisciplinary system. To illustrate the lack of a central directive, consider for example two researchers engaged in similar research problems but affiliated to different institutions and located in different geographic regions. Though differing local restrictive parameters or incentive structures may arise based on these researchers’ academic affiliations, grant requirements and other associated externalities, these externalities are not centrally imposed on the multidisciplinary system, but only on the individual.

Secondly, autonomy is fostered by disciplinary differences, along with associated linguistic heterogeneity as discussed by Bernstein (2003), whereby stigmergy between researchers remains characteristically weak, especially at a systems level of analysis. Despite individual researchers being highly
vulnerable to the influence of externalities due to the openness of a complex system as discussed by Cilliers (2001), the weakness of stigmergy between researchers supports local autonomy in ensuring that externalities impacting the individual researcher are unable to make large perturbations within a system. Finally, and perhaps most critically, local autonomy and differentiation in terms of research aims and selected methodologies are greatly incentivized by the emphasis that peer-reviewed scientific journals place on novelty. Thus, researchers are actively deterred from following in the exact footsteps of their predecessors. The lack of a centralized directive, cross-disciplinary linguistically differences and the novelty incentive allow individual agents to remain largely locally autonomous regarding research aims and influences from within the system.

Unconcealment

From the discussion above, it is at this point deemed quite clear how an array of goal-orientated researchers in multiple disciplines working on the same metaproblem whilst receiving stigmergy from various sources (i.e. the metaproblem, other researchers and the environment) may be conceptualized as a complex system exhibiting an emergent form of swarm intelligence in fulfilling its teleological (research) purpose. We propose that this emergent intelligence expresses itself in the unconcealment of the ‘form’ of the metaproblem. Unconcealment is not deemed to be in conflict with the correspondence theory of truth as discussed by Wrathall (2010). Rather, unconcealment is to be understood more as the process of revealing, or even discovery, and thereby concerned with the analysis of broad contexts (Wrathall, 2010). Indeed, propositional truth may to some extent be understood as being conditional to the broader context and scope of unconcealment, as noted by Wheeler (2020). Therefore, the application of simple propositional truth within the context of resolving a metaproblem is deemed too narrow in describing the functionality of a multidisciplinary system. This is especially clear when considering conflicting disciplinary ontologies and epistemologies contained within a multidisciplinary system and in relation to areas of research where the correspondence theory of truth may not be suitable, notably questions of ethics (David, 2020). Furthermore, error is as much a part of unconcealment, as error, in so far as it is the opposite of truth, is revealing as to the subject of inquiry (Heidegger, 2013), or the form of the metaproblem. Therefore, we propose that a multidisciplinary research system is involved in an ontological process of seeking to unconceal the true form of its topic of inquiry, independent of presuppositions.

The final step in our ontology of a multidisciplinary research system involves the iterative quality of the research process, that is, the unconcealment of the metaproblem, which very much goes hand in hand with the dynamic routes of inquiry as discussed above. The idea of considering research as an iterative process has been mentioned in various disciplines. Finlay (2012), for example, describes phenomenological research as an unfolding phenomenon of ‘seeing afresh’; Kerssens-van Drongelen (2001) in turn proposes a model for the research process called the ‘iterative theory-building process’ whereby a key feature of Kerssens-van Drongelen (2001)’s model is that research questions are allowed to change over time, which is in line with the dynamic routes of inquiry as discussed above; Hardwick and Marsh (2012) explicitly highlights the iterative nature of falsification in science. Through multiple cycles of unconcealment, we therefore suggest that the process of iterative questioning and reorientation inherent to the multidisciplinary research system will progressively unconceal the form of the metaproblem. Because unconcealment is a process that is expressed at the level of the system rather than the individual researcher, it may be deemed to be a form of strong emergence as discussed by Bar-yam (2004).

A visual conceptualization of a multidisciplinary research system is provided in Figure 1 where the green dotted lines represent the dynamic routes of inquiry followed by researchers/actors (A), towards concise but fragmentary solutions (S). Black lines (numbered 2) signify systemic stigmergy arising from other researchers in the field and also from solutions obtained during the research process. Stigmergy arising from a direct research result is illustrated by a solid black line indicative that such an orientation signal is likely to have a significant impact on a researcher’s orientation, whereas stigmergy between multidisciplinary researchers is illustrated by a dotted black line indicated of the relative weakness of such feedback.

Multidisciplinary Approaches to Renewable Energy Research

This section aims to provide an empirical example of how a multidisciplinary system as conceptualized above has emerged in the practice of renewable energy research.

Preference for renewable energy sources for electricity generation has emerged globally (REN21, 2017) due to various problems associated with traditional fossil fuels, along with increasing trends in global energy consumption. To facilitate an energy transition, renewable energy research has emerged as an area that is primed for collaborative research. It has been observed that established fields of research functioning within established paradigms tend to be more prone to collaborative research than emergent fields; so too were data-driven fields such as physics and chemistry observed to be more prone to collaborative research than word-driven fields such as history and philosophy (Baldwin & Austin, 1995). Renewable energy research is thereby typical of the research fields that are disposed towards collaborative research: it is essentially a data-centric discipline; and though it is a developing field, it has largely adopted the research paradigms established by engineering and to a lesser extent natural– and computer sciences. It may be tempting to understand renewable energy research as an integrated code with lateral relations to...
established disciplines, where the boundaries between these disciplines are becoming fragile leading to integration. Indeed, the larger societal context of the energy transition (or the metaproblem) is furthermore coupled to the social, economic and environmental pillars which result in strong externalities shaping and integrating the research narrative. It is anticipated that such a weakening of disciplinary boundaries may lead to disciplinary crosspollination and set up conditions for interdisciplinary research, as opposed to multidisciplinary research. However, we contend that to date, this integration has not fully come to fruition and that renewable energy research can largely be understood in terms of the multidisciplinary research system conceptualized above.

Figure 2 was produced from the Shape of Science interactive visualization tool on the Scimago Journal & Country Rank (SJ&CR) website. The Shape of Science tool provides a topological representation of the degree of similarity between international research journals which is reflected by their spatial proximity on the map – that is, journals which are closely related are topographically clustered closely together (Hassan-Montero et al., 2014). The level of similarity between journals was quantified by considering their citation relationship, the details of which may be found in the article by Hassan-Montero et al. (2014). This citation relationship between journals is interpreted as quantifiable evidence of stigmergy between disciplines, whereby the topological distance between journals, as seen in Figure 2, is considered a measure of the strength or weakness of the stigmergy between individual journals and disciplines. Within this context, publications are also understood as that which provides the system with memory as required by Cilliers (2001). Figure 2 (right) shows the spread of journals identifying with the SJ&CR category ‘Renewable Energy, Sustainability and Environment’, within the context of larger research discipline spatial topology. The scattered spread of these journals indicates that high levels of cross-citations are not taking place across disciplinary boundaries, which is in keeping with the essentially non-cooperative aspect of multidisciplinary research. Consider, for example, the topographic distance between Energy and Environmental Science (which is more based in the disciplines of Physics and Chemistry) and Strategic Planning for Energy and the Environment (which is more based in the disciplines of Business Management and Social Sciences). Despite both these journals being united in their orientation towards their object of inquiry – that is, renewable energy research – and acknowledging the multidisciplinary nature of the metaproblem, a strong disciplinary separation between these journals, as evidenced by cross-citations between them, remains evident. This implies within the sphere of peer-reviewed academic publications, a multidisciplinary research approach rather than an interdisciplinary research approach is being adopted, as contended above.

This analysis has implications for the future, not only of renewable energy research, but of the metaproblem it ostensibly encapsulates: the question of affordable and clean energy on a global scale (articulated clearly as one of the
United Nations Sustainable Development Goals). In pursuit of solutions to complex socio-economic and technical problems, such as the energy question, global policy indicates a clear need for forms of collaboration which place the metaproblem first. The dilemma presented by current multidisciplinary research approaches is that such structures are likely to demonstrate greater allegiance to individual disciplines and specializations – in other words, the research becomes self-serving. This is typical of siloed disciplines in a collection code (Bernstein, 2003) configuration, where the objective is survival and progress of the discipline itself. The irony is that a significant number of the sub-disciplines in renewable energy research are emergent (and even nascent) specializations, which would be described in Bernsteinian terms as ‘regionalizations’ (2000) – combinations of pure disciplines – which usually results in greater cross-pollination, lateral relations and a weakening of disciplinary boundaries. However, regionalization processes threaten disciplinary survival, and emergent fields (such as renewable energy) are more likely to follow self-serving survival strategies than risk the boundary-blurring implications of collaborative allegiance to the metaproblem. Understanding that this is a natural process for ontological and epistemological disciplinary development raises questions around the assumption that metaproblems can be approached in fairly simple collaboration structures.

Conclusions

This article seeks to develop a fundamental ontology for a multidisciplinary research system, drawing from complexity and systems theory, organizational dynamics and certain concepts within the philosophy of science. The semi-axiomatic point of departure within our ontology, which may also be considered as a set of preconditions, is firstly in recognizing the research process as being teleological in its purpose, based on the opposing dyad between the autonomous researcher and the researcher’s purpose – that is, researching a problem. Secondly, disciplinarity is understood as a restricted language code as noted by Bernstein. As researchers are constrained in a certain sense by disciplinary bounds, the scope of certain problems, termed metaproblems, exceeds these disciplinary bounds, thereby creating the impetus for a collaborative research system. This unity of purpose amongst researchers serves as the inception point of this system.

Such a collaborative research system, we argue, may be considered a complex system in terms of its features and dynamics. Therein our conceptualization of a multidisciplinary research system departs significantly from what is deemed to be the consensus position. We argue that communications within a multidisciplinary research system can be seen as orientation signals – or stigmergy – which is very much analogous to communication within a swarm and is functional in self-organization. We note that though stigmergy from outside the system (externalities) may strongly influence the individual researcher, stigmergy between researchers within the system remains weak due to disciplinary restrictions of language codes, which is an essential feature of the system’s robustness in maintaining its purpose. Therefore, disciplinary silos (or language codes), which are often criticized for their restrictiveness, are somewhat paradoxically seen as instrumental in maintaining the researcher’s autonomy and the system’s robustness. System memory, it is argued, manifests itself in the ability of a researcher to change her/his route of inquiry, based on environmental feedback, whereby new information becomes incorporated into the adjusted research methodology. We propose that an emergent intelligence, at the level of the system, expresses itself in the
unconcealment of the ‘form’ of the metaproblem. It was finally illustrated that in practice, collaboration within the renewable energy research has developed by processes explained in this article into a multidisciplinary approach, at least with regard to academic publications.

This article intends to improve our understanding of the system(s) within which researchers from multiple disciplines work on societal metaproblems, by seeking to describe the principles and dynamics of such a research system at a fundamental level of analysis. It is anticipated that an improved understanding of multidisciplinary research systems would provide key role players with insights into certain strengths particular to less integrated and self-organized forms of collaborative research and with a framework with which to improve the design and fostering of such systems. This article is the first in a series of three dealing with collaborative research systems. The second article deals with interdisciplinary research systems and the third the interactions between collaborative research systems, which is often described as transdisciplinary.

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**References**

Abraham, A., Guo, H., & Liu, H. (2006). Swarm intelligence: foundations, perspectives and applications. *Studies in Computational Intelligence*, 26, 3-25.

Alvargonzález, D. (2011). Multidisciplinarity, interdisciplinarity, transdisciplinarity, and the sciences. *International Studies in the Philosophy of Science*, 25(4), 387-403. https://doi.org/10.1080/02698595.2011.623366.

Baldwin, R. G., & Austin, A. E. (1995). Toward greater understanding of faculty research collaboration. *The Review of Higher Education*, 19(1), 45-70. https://doi.org/10.1353/rhe.1995.0002.

Balsiger, P. W. (2004). Supradisciplinary research practices: history, objectives and rationale. *Futures*, 36(4), 407-421.

Bar-yam, Y. (2004). A mathematical theory of strong emergence using multiscale variety. *Complexity*, 9(6), 15-24.

Bernstein, B. (1975). Class and pedagogies: Visible and invisible. *Educational Studies*, 1(1), 23-41.

Bernstein, B (2000) *Pedagogy, symbolic control, and identity: theory, research, critique* (Vol 5). Lanham: Rowman & Littlefield.

Bernstein, B. (2003). *Class, codes and control volume II applied studies towards a sociology*. London: Routledge.

Bernstein, J. H (2015). Current issues how does access to this work benefit you? Let us know! Transdisciplinarity: a review of its origins, development, and current issues. *Journal of Research Practice*, 11(1), 28.

Bonabeau, E., Dorigo, M., Marco, D. D. R. D. F., Theraulaz, G., & Théraulaz, G. (1999). *Swarm intelligence: From natural to artificial systems*. Oxford: Oxford University Press.

Bruce, A., Lyall, C., Tait, J., & Williams, R. (2004). Interdisciplinary Integration in Europe: the Case of the fifth framework Programme. *Futures*, 36(4), 457-470.

Castaño, X., & Oliveira, N. (2020). Collaboration, coordination, and cooperation among organizations: Establishing the distinctive meanings of these terms through a systematic literature review. *Journal of Management*, 46(6), 965-1001. https://doi.org/10.1177/0149206320901565.

Choi, B. C. K., & Pak, A. W. P. (2006). Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: I. Definitions, objectives, and evidence of effectiveness. *Clinical and Investigative Medicine*, 29(6), 351-364.

Cilliers, P. (2001). Boundaries, hierarchies and networks in complex systems. *International Journal of Innovation Management*, 5(2), 135-147.

Claveau, F., & Fernández, M. V. (2015). Epistemic contributions of models: conditions for propositional learning. *Perspectives on Science*, 23(4), 405-422. https://doi.org/10.1162/POSC.

Collin, A. (2009). Multidisciplinary, interdisciplinary, and transdisciplinary collaboration: implications for vocational psychology. *International Journal of Educational and Vocational Guidance*, 9, 101-110. https://doi.org/10.1007/s10775-009-9155-2.

David, M (2020). The correspondence theory of truth. In E. N. Zalta (Ed), The [Stanford] Encyclopedia of Philosophy (Winter 202). Stanford: Metaphysics Research Lab, Stanford University.

Fawcett, J. (2013). Thoughts about multidisciplinary, interdisciplinary, and transdisciplinary. *Nursing Science Quarterly*, 26(4), 376-379. https://doi.org/10.1177/0894318413500408.

Fertig, E., Apt, J., Jaramillo, P., & Katzenstein, W. (2012). The effect of long-distance interconnection on wind power variability. *Environmental Research Letters*, 7(3), 34017.

Finlay, L. (2012). Unfolding the phenomenological research process: iterative stages of “seeing afresh.” *Journal of Humanistic Psychology*. https://doi.org/10.1177/0731978412453877.

Goldfarb, B (2008). The effect of government contracting on academic research: does the source of funding affect scientific output?. *Research Policy*, 37, 41-58. https://doi.org/10.1016/j.respol.2007.07.011.

Greville, H., Haynes, E., & Kagie, R. (2019) ‘It Shouldn’t Be This Hard’: exploring the challenges of rural health research.
Gulbrandsen, M., & Smeby, J. (2005). Industry funding and university professors’ research performance. *Research Policy*, 34, 932-950. https://doi.org/10.1016/j.respol.2005.05.004.

Hara, N., Solomon, P., Kim, S. L., & Sonnenwald, D. H. (2003). An emerging view of scientific collaboration: Scientists’ perspectives on collaboration and factors that impact collaboration. *Journal of the American Society for Information Science and Technology*, 54(10), 952-965. https://doi.org/10.1002/asi.10291.

Hardwick, D. F., & Marsh, L. (2012). Science, the market and iterative knowledge. *Studies in Emergent Order*, 5, 26-44.

HarperCollins Publishers Limited (2020). *Collins online dictionary*. Glasgow: HarperCollins Publishers.

Hassan-Montero, Y., Guerrero-Bote, V., & De-Moya-Anegón, F. (2014). Graphical interface of the SCIMAGO Journal and Country Rank: an interactive approach to accessing bibliometric information. *Profesional de La Informacion*, 23(3), 272-278. https://doi.org/10.3145/epi.2014.may.07.

Heidegger, M. (2013). *The essence of truth: On Plato’s cave allegory and theaetetus*. London: Bloomsbury Publishing.

Heylighen, F. (2016). Stigmergy as a universal coordination mechanism I: definition and components. *Cognitive Systems Research*, 38, 4-13. https://doi.org/10.1016/j.cogsys.2015.12.002.2016.

Hirth, L. (2020). The market value of variable renewables the effect of solar wind power variability on their relative price. *Energy Economics*, 38, 218-236. https://doi.org/10.1016/j.eneco.2013.02.004.2013.

Hord, S. M. (1986). A synthesis of research on organizational collaboration. *Educational Leadership*, 43(5), 22-26.

Hunter, L., & Leahey, E. (2017). Collaborative research in sociology: trends and contributing factors author (s): Laura Hunter and Erin Leahey source. *The American Sociologist*, 39(No. 44), 290-306. https://doi.org/10.1017/s12108-008-9042-4.

Jantsch, E. (1972). Inter- and transdisciplinary university: a systems approach to education and innovation. *Higher Education, I*(1), 7-37. https://doi.org/10.1007/BF01956879.

Jerneck, A., Olsson, L., Ness, B., Anderberg, S., Baier, M., Clark, E., Hickler, T., Hornborg, A., & Persson, J. (2011). Structuring sustainability science. *Sustainability Science*, 6, 69-82. https://doi.org/10.1007/s11625-010-0117-x.

Kauffman, D., Kuenzler, J., & Sager, F. (2020). How (not) to design and implement a large-scale, interdisciplinary research infrastructure. *Science and Public Policy*, 6, 5-58.

Kerssens-van Drongelen, I. (2001). The iterative theory-building process: rationale, principles and evaluation. *Management Decision*, 9, 25-42.

Klein, J. T. (2008). Evaluation of interdisciplinary and transdisciplinary research. *American Journal of Preventive Medicine*, 35, 116-123. https://doi.org/10.1016/j.amepre.2008.05.010.

Ladnyman, J., & Lambert, J. (2013). What is a complex system?. *European Journal for Philosophy of Science*, 3, 33-67. https://doi.org/10.1007/s13194-012-0056-8.

Massey, C., Alpass, F., Flett, R., Lewis, K., Morriss, S., & Sligo, F. (2006). Crossing fields: the case of a multi-disciplinary research team. *Qualitative Research, 6*(2), 131-147.

Milchram, C., Märker, C., & Hake, J.-F. (2019). The role of values in analyzing energy systems: insights from moral philosophy, institutional economics, and sociology. *Energy Procedia*, 158, 3741-3747.

Morrow, W. (2015). *Bounds of democracy: Epistemological access in higher education*. Cape Town: HSRC Press.

Nersessian, N. J. (2019). Interdisciplinarieties in action: cognitive Ethnography of bioengineering sciences research laboratories. *Perspectives on Science*, 22(3), 397-417. https://doi.org/10.1162/POSC.

Nissen, L. A. (1997). *Teleological language in the life sciences: Lowell Nissen*. Rowman & Littlefield.

Perlman, M (2004). The modern philosophical resurrection of teleology the modern philosophical resurrection of teleology. *The Monist, 87*(1), 3-51.

Pettis, J., Owens, S., & Bulkeley, H. (2008). Crossing boundaries: interdisciplinarity in the context of urban environments. *GeoForum, 39*(2), 593-601.

Prasad, A., Segarra, P., & Villanueva, C. E. (2019). Studies in higher education academic life under institutional pressures for AACSB accreditation: insights from faculty members in Mexican business schools accreditation: insights from faculty members in Mexican business. *Studies in Higher Education, 44*(9), 1605-1618. https://doi.org/10.1080/03075079.2018.1458220.

REN21 (2017). *Renewables 2017 global status report*. Cape Town: REN21.

Rose, H. (2019). Dismantling the ivory tower in TESOL: a renewed call for teaching-informed research. *TESOL Quarterly*. https://doi.org/10.1002/tesq.517.

Salvato, C., Reuer, J. J., & Battigalli, P. (2014). Cooperation across disciplines: a multilevel perspective on cooperative behavior in governing interfirm relations. *Academy of Management Annals, 8*(1), 960-1004.

Sanderson, D. (1996). Cooperative and collaborative mediated research. *Computer Networking and Scholarly Communication in the 21stCentury University, 1*, 95–114.

Steven, C. J., Fraser, I., Mitchley, J., & Thomas, M. B. (2007). Making ecological science policy-relevant: issues of scale and disciplinary integration. *Landscape Ecology*, 22(6), 799-809.

Stichweh, R. (2008). The sociology of scientific disciplines: on the sociology of scientific disciplines: on the genesis and stability of the disciplinary structure of modern science. *Science in Context*, 3-15. https://doi.org/10.1017/S0269889700001071.

Stock, P., & Burton, R. J. F. (2011). Defining terms for integrated (Multi-Inter-Trans-Disciplinary) sustainability research. *Sustainability, 3*, 1090-1111. https://doi.org/10.3390/su3081090.
Sumpter, D. J. T., & Beekman, M. (2003). From nonlinearity to optimality: pheromone trail foraging by ants. *Animal Behaviour, 66*, 273-280. https://doi.org/10.1006/anbe.2003.2224.

Takahashi, M., Indulska, M., & Steen, J. (2018). Collaborative research project networks: knowledge transfer at the fuzzy front end of innovation. *Project Management Journal, 49*(4), 36-52. https://doi.org/10.1177/8756972818781630.

Taylor, M. C. (2009). *End the university as we know it* (pp. 27-29). New York: The New York Times.

Tian, M., & Lu, G. (2017). Teaching in higher education what price the building of world-class universities? Academic pressure faced by young lecturers at a research-centered university in China. *Teaching in Higher Education, 22*(8), 957-974. https://doi.org/10.1080/13562517.2017.1319814.

Tress, G., Tress, B., & Fry, G. (2007). Analysis of the barriers to integration in landscape research projects. *Land Use Policy, 24*(2), 374-385.

Uwizeyimana, D. E., & Basheka, B. C. (2017). The multidisciplinary, interdisciplinary and trans-disciplinary nature of public administration: A methodological challenge?. *African Journal of Public Affairs, 9*(9), 1-28.

Vanasupa, L., Schlemer, L., Burton, R., Brogno, C., Hendrix, G., & Macdougall, N. (2014). Laying the foundation for transdisciplinary faculty collaborations: actions for a sustainable future. *Sustainability, 6*, 2893-2928. https://doi.org/10.3390/su6052893.

Wang, S., & Wang, S. (2020). Impacts of wind energy on environment: a review. *Renewable and Sustainable Energy Reviews, 49*, 437-443. https://doi.org/10.1016/j.rser.2015.04.137.2015.

Weinberger, D (2011). *Too big to know: Rethinking knowledge now that the facts aren’t the facts, experts are everywhere, and the smartest person in the room is the room*. New York, NY: Basic.

Westley, F. R., Tjornbo, O., Schultz, L., Olsson, P., Folke, C., Crona, B., & Bodin, Ø. (2013). A theory of transformative agency in linked social-ecological systems. *Ecology and Society, 18*(3).

Wheeler, M. (2020). Martin heidegger. In E. N. Zalta (Ed), The *[Stanford] Encyclopedia of Philosophy (Fall 2020)*. *Metaphysics Research Lab*. Stanford: Stanford University.

Wrathall, M. A. (2010). Heidegger and truth as correspondence. *International Journal of Philosophical Studies, 2559*. https://doi.org/10.1080/096725599341974.1999.

Wray, K. B. (2012). The epistemic significance of collaborative research. *Philosophy of Science, 69*(1), 947-967. https://doi.org/10.1017/s11098-015-0537-7.

Young, M., Sørensen, M. P., Bloch, C., & Degn, L. (2017). Systemic rejection: political pressures seen from the science system. *Higher Education, 74*(3), 491-505. https://doi.org/10.1007/s10734-016-0059-z.

Zhang, S., Lee, C. K. M., Chan, H. K., Choy, K. L., & Wu, Z. (2015). Swarm intelligence applied in green logistics: a literature review. *Engineering Applications of Artificial Intelligence, 37*, 154-169. https://doi.org/10.1016/j.engappai.2014.09.007.