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Repertoires:

A Post-Kuhnian Perspective on Scientific Change and Collaborative Research

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Abstract

We propose a framework to describe, analyze, and explain the conditions under which scientific communities organize themselves to do research, particularly within large-scale, multidisciplinary projects. The framework centers on the notion of a research repertoire, which encompasses well-aligned assemblages of the skills, behaviors, and

material, social, and epistemic components that a group may use to practice and manage certain kinds of science and train newcomers, and whose enactment affects the methods and results of research. This account provides an alternative to the idea of Kuhnian paradigms for understanding scientific change in the following ways: (1) it does not frame change as primarily generated and shaped by theoretical developments, but rather takes account of administrative, material, technological, and institutional innovations and explicitly questions whether and how such innovations accompany, underpin, and/or undercut theoretical shifts; (2) it thus allows for tracking of the organization, continuity, and coherence in research practices which Kuhn characterized as 'normal science' without relying on the occurrence of paradigmatic shifts and revolutions to be able to identify relevant components;
and (3) it requires particular attention be paid to the performative aspects of science, whose study Kuhn pioneered but which he did not extensively conceptualize. We provide a detailed characterization of repertoires and discuss their relationship with communities, disciplines, and other forms of collaborative practices within science, building on an analysis of historical episodes and contemporary developments in the life sciences, as well as cases drawn from social and historical studies of physics, psychology, and medicine.

Keywords: scientific change, collaboration, scientific practice, big science, research organization, paradigm.

1. Introduction

A vast body of scholarship in the history, philosophy,,and social studies of science underscores the critical role of collaboration in the development of scientific knowledge (to name just a few examples, see Griesemer and Gerson 1993; Wray 2001, 2002; Hackett 2005; Shrum, Chompalov, and Genuth 2007; Gerson 2009; Andersen 2010, 2016; Gorman ed. 2010).[1] Many forms of scientific collaboration have been documented and analyzed, including co-located and dispersed, short and long-term, virtual and in-person, large and small scale, and even voluntary and involuntary (Nersessian 2006; Felt ed. 2009; Parker, Vermeulen, and Penders eds. 2010; MacLeod and Nersessian 2013). Collaboration often involves individuals with different skills, training, and goals, who are not co-located and who, even when working toward common goals, are subject to diverse institutional, cultural, and financial pressures, particularly in the contemporary context of 'big science' carried out through multidisciplinary projects occurring within international networks (Price 1965; Hughes 2002; Davies, Frow, and Leonelli 2013). It is clear from existing scholarship that research groups and communities have variable degrees of continuity, longevity, and durability, depending on their relation to existing knowledge, materials, technologies, and institutions, as well as on the social dynamics within and beyond their boundaries (Galison 1997; Knorr-Cetina 1999; Latour 1987).

[1] In this paper we are not considering the extensive philosophical literature on social epistemology or more theoretical literature on collaboration from the philosophy of science in any detail, but focus on that literature most relevant from a philosophy of science in practice point of view (Ankeny et al 2011). Making a link between formal treatments and our historically informed account is an important task, but one that lies beyond the scope of this paper.

Furthermore, it is evident that the organization of research communities, and the ways in which they are constructed and managed, has a major impact on the quality and types of outputs that are produced (Solomon 2001; Longino 2002; Wray 2002; Rolin 2008).

Philosophers of science have paid some attention to the organization of research and its epistemic implications. Some philosophers have analyzed the mechanisms that underlie collaborative work, focusing particularly on the division of labor involved (Thagard 1997), the use of theories, models, and tools as conduits to communication and integration (Star and Griesemer 1989; Nersessian 2009), and the typologies and patterns of epistemic dependence involved in the distribution of cognitive labor among interdisciplinary collaborators (Andersen and Wagenknecht 2013, Andersen 2016).[2]

However, there is still relatively limited philosophical work on what constitutes a research community, how communities change over time, and how the development of collaborations relates to the production and development of knowledge within the various social, cultural, institutional, and economic environments in which scientific research occurs.[3] In other words, philosophers of science have hitherto paid little

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[2] Detailed discussions of integration also are provided by Mitchell (2009) under the heading of 'integrative pluralism'; Chang (2012) in his discussion of the three modalities through which systems of practice can interact to produce knowledge, one of which is integration; and the contributors to a special section on integration (Brigandt ed. 2013), particularly Gerson (2013) on organizational mechanisms.

[3] We do not attempt to define which parts of scientific practice are 'external' or 'internal' to it, as this distinction is often very arbitrary (see Shapin 1992) and is

attention to collaboration, and more generally the social organization of research, as a gateway to think about scientific change.

Existing characterizations of communities in terms of shared theories - which in turn constitute a discipline or field, and which can be challenged and reconstituted depending on conceptual shifts - have greatly enhanced our understanding of the dynamics of scientific change and how to account for research 'progress' (e.g., Kuhn 1962; Toulmin 1972; Shapere 1977; Darden and Maull 1977). However, these accounts have limited value for making sense of multidisciplinary efforts, where successful collaboration involves the harmonious merging of different types of expertise and disciplinary training. Most importantly for our purposes, they also fail to account for the critical roles played by social, political, and economic factors in the development and outcomes of research practices, and for the observation (often made within historical and social studies of science) that scientific innovations can take many forms other than the advancement of new theories or concepts, and are not necessarily tied to paradigmatic shifts.

In this paper, we propose a framework for analyzing the emergence, development, and evolution of collaborations in science that we believe will facilitate philosophical analysis and explanation of critical questions around the functioning, flexibility, durability, and longevity of research groupings and their outputs. We are particularly interested in tracing the material, social, and epistemic conditions under which individuals are able to join together to perform projects and achieve common goals, in ways that are relatively robust over time despite environmental and other types of

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unnecessary for our arguments; see also Longino's rejection (2002) of the usual distinction made between the 'social' and the 'rational.'

changes, and can be transferred to and learnt by other groups interested in similar goals. We refer to these conditions, which include ways to wield and align specific skills and behaviors with appropriate methods, epistemic components, materials, resources, participants, and infrastructures, as *repertoires*. We argue that the creation or adoption of one or more repertoires has a strong influence on the identity, boundaries, practices and outputs of research groups, whether their individual members explicitly recognize this impact or not. At the same time, a repertoire is not a necessary condition for the production of scientific knowledge and/or the emergence of stable and/or coherent research communities. Indeed, not all such communities have a repertoire, and many creative and innovative scientific initiatives grow at the margins of, or in outright opposition to, the most long-lived repertoires, with significant consequences in terms of their visibility, reputation and resources.

This argument builds on empirical insights by historians and philosophers of science on practices within contemporary research communities in the experimental life sciences, as well as cases drawn from social and historical studies of other sciences including physics, psychology, and medicine. We analyze the parallels and dissimilarities between our approach and philosophical discussions of scientific change, and discuss in detail the characteristics, composition, and performative nature of repertoires. We then reflect on what it means for a repertoire to be resilient and transferrable, the relationship between repertoires and research groups, and the significance of the alignment of repertoire components in terms of evaluating the success and longevity of particular repertoires and its broader epistemic and social implications. Finally, we discuss the scope of repertoires and their usefulness as methodological frameworks for philosophers to reconstruct, compare, and evaluate scientific strategies and developments across time, space, cultures, and disciplines, without being forced to focus solely or primarily on examples involving substantial theoretical change.

2. Paradigms versus Repertoires: Capturing Performance

In his seminal work *The Structure of Scientific Revolutions* (1962), Thomas S. Kuhn uses the term ‘paradigm’ to identify activities that are simultaneously conceptual, social, and material and that are constitutive of research communities, and points to ‘revolutionary’ paradigmatic shifts as ways to identify and circumscribe such activities into coherent and stable assemblages. This intertwining of conceptual, social, and material factors in research is a core idea that serves as a starting point for our own analysis. However as many commentators have observed, paradigms are not very useful as a framing concept particularly for the analysis of contemporary science. First, they are highly static and inflexible entities in which change only occurs in dramatic fashion. This conceptualization of scientific change does not adequately capture the dynamic nature and pace of scientific practice, nor does it do justice to the shifts in technology, theorizing, and methods happening within research communities at any specific point in time (Galison 1997; Hoyningen-Huene 2013). Second, conflicting paradigms are considered by Kuhn to be incommensurable, which implies that the adoption of a paradigm results in the exclusion of any possible alternative except in extreme moments of crisis. In contrast, researchers can and do move between different approaches and models of work, depending on circumstances, including making smaller-scale changes and using more than one approach simultaneously (Fleck 1979 [1935]; Giere 2006; Griesemer 2006; MacLeod and Nersessian 2013; Gerson 2013).

Third, as historians have noted, Kuhn's account and his choice of case studies gives undue primacy to theoretical knowledge as primary output of science, with major theoretical shifts (such as those involved in the Copernican revolution) functioning as a means to identify major developments within science and develop historical and philosophical narratives about scientific change more generally. Because of this assumption, and despite Kuhn's own deep awareness of the significance of material and social aspects of research, the idea of a 'paradigm' does not provide guidance for those who wish to investigate and analyze the critical roles of shifts in technologies, social and institutional resources and infrastructures, and procedures and norms specifically aimed at stimulating institutional and financial support for science.[4] This rather narrow focus encourages an excessively internalistic view of scientific practice,[5] in which strategies and activities aimed at attracting and retaining material, human, economic, and political resources tend to be viewed as external to the processes of scientific research, and may be acknowledged as significant only when they directly shape the content of the propositional knowledge derived from these processes.. In contrast, we contend that consideration of what results from research needs to encompass a much wider range of phenomena including technological innovations, data generation, the production of new models and visualization techniques, and novel ways to organize, manage, and support research communities. Thus decisions and strategies concerning funding as well as the management and

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[4] Lakatos's views on research programmes (1970), though much less inflexible concerning the degree of changes happening within any given programme, are susceptible to similar critiques.

[5] This interpretation is one that Kuhn himself would likely endorse (Kuhn 2000, 287). On Kuhn's internalism, see especially Wray 2010.

dissemination of resources and outputs (among other factors) are as scientifically and epistemologically significant as decisions and reasoning about theory, methods, instrumentation, technologies, and models, as well as the types of expertise and compositions of the groups tasked with performing research.[6]

Hence we introduce the notion of 'repertoires,' which we define as the well-aligned assemblages of skills, behaviors, and material, social, and epistemic components that a group may use to practice certain kinds of science, and whose enactment affects the methods and results of research, including how groups practice and manage research and train newcomers.

The term repertoire comes from the French *répertoire*, which in turn derives from the Latin *repertorium* (*repertorio* in Italian). The original and narrow etymology, which resonates with contemporary common usage of the term, refers to "listing, catalogue, inventories" that can help one to find items easily without necessarily having been involved in collecting the relevant materials in the first place. The term then was adopted by performing artists, particularly actors and musicians, starting from the mid-19th century in Italy and France as a way to refer simultaneously to the works they performed *and* the abilities and skills through which they could be reproduced,

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[6] Our view aligns well with Hasok Chang's pragmatist reading of knowledge (including scientific knowledge) as the ability to perform given epistemic activities (Chang 2013), and with the interpretation of naturalism as principal philosophical approach to the study of scientific practice recently defended by Joseph Rouse (2015): "The ongoing practice of scientific research encompasses the relevant form of scientific understanding; efforts to extract a substantive body of knowledge from that practice are among the philosophical impositions upon science that naturalists should reject" (7).

together with the unique characteristics of specific enactments of the works. The term thus acquired an increasingly performative quality, and is currently used in French, English, and Italian to refer to the constellation of knowledge, resources, and abilities needed to be able to engage in a specific type of performance.[7] The Oxford English Dictionary now defines a 'repertoire' in two main ways: as the "body of items that are regularly performed" and as the "stock of skills or types of behavior that a person habitually uses." In our analysis, we exploit the complementary character of these two definitions of 'repertoire.' On the one hand, scientific repertoires include material and conceptual elements, such as specific technologies, methods, and theories. Indeed, the adoption and use of instruments and concepts is a crucial step within the establishment of a repertoire, which is why many 20th century philosophers have identified these elements as core components of research programs (e.g., Bachelard 1978 [1934]; Lakatos 1970; Laudan 1977). On the other hand, a repertoire only emerges when scientists establish what they perceive to be reliable and effective ways to work with these ideas and materials within and across groups, which typically means developing social structures, ways of distributing labor, norms, skills, and behaviors. Most importantly, the development of a repertoire involves the elaboration of strategies for coordinating and managing these conceptual, material, and social components, so that when they are combined, they produce the intended performance.[8] Repertoires are thus not simply inventories of elements that need to be

[7] We are here defining 'performativity' as the agency involved in materially realizing propositional and/or embodied knowledge, for instance when uttering a sentence in reply to a question, or performing an action to achieve a particular goal.

[8] The emphasis on performative aspects of scientific practice distinguishes our usage from Gilbert and Mulkay's interpretation (1984) of 'repertoires' as primarily or solely

combined in order to be able to conduct a given type of project, and/or achieve a given epistemic goal; crucially, they include knowledge of how to align such inventories of elements so that they can be effectively used to acquire the resources, capacities, and expertise needed to pursue an inquiry.

The idea of repertoire thus characterized bears marked similarities to Kuhn's notion of 'exemplars' as models for how to perform research. At the same time, Kuhn does not take exemplars to include social, institutional, and economic features, and treats them primarily as pedagogical tools that play key roles in scientific training rather than research (which also explains why exemplars do not figure prominently in his account of paradigms as units of scientific change). By contrast, we view repertoires as key components of much cutting-edge scientific practice, an understanding that brings our views closer to Ludwik Fleck's discussions (1979 [1935]) of 'thought styles' and particularly teamwork.[9]

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about discourse, and also from the focus by Rip and Talma (1998) on repertoires as patterns reproduced particularly in debates around new and emerging technologies. As they retain flexibility vis-à-vis historical and scientific developments and also incorporate both social and epistemic elements, our understanding of 'repertoire' also is different than that typically used in social movements and political theory. For instance our usage is more inclusive than Swidler's (1986) which is intended as an antidote to Weberian views on culture, which sees repertoires as the source of a 'tool kit' of symbols, stories, rituals, and world-views from which actors can select different elements to shape their actions.

[9] In Fleck's terms, 'team work' is not simply an additive process of individual activities which contribute to the whole (1979 [1935], 99), but functions via a range of cooperative practices. He explicitly uses metaphors from the performing arts

Another fruitful philosophical notion which informs our framework is Hasok Chang's 'systems of practice,' which he defines as "a coherent set of epistemic activities performed with a view to achieve certain aims" (2012, 15), where epistemic activities are "a more-or-less coherent set of mental and physical operations that are intended to contribute to the production or improvement of knowledge in a particular way, in accordance with some discernible rules (though the rules may be unarticulated)" (16). While this account of epistemic activities is fully compatible with our views, note that Chang is primarily interested in analyzing the intellectual and material conditions within which scientific claims can be produced, evaluated, and understood. As a consequence, he pays less attention to the performative, social, financial, and organizational components involved in the establishment, evolution, and reproduction of particular ways of doing research. Our notion of repertoire is therefore broader than his system of practice, with each repertoire potentially involving one or more such systems, as well as practices that play prominent roles in shaping the nature and results of scientific knowledge production, and yet are not epistemic in Chang's definition (i.e., they may not be intended to contribute to the development of knowledge claims, and even when they do, it may not always be possible to define the rules through which this happens). Similarly, Hans-Jörg Rheinberger's analysis (1997) of how research communities are built around and develop experimental systems is complementary to ours, since these systems are often crucial components of repertoires and Rheinberger insists on the importance of practices and related know-how as key research outputs. However, his account focuses primarily on the

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including the playing of an orchestra; however his discussion focuses solely on the epistemic aspects of scientific practice in relation to 'thought styles.'

management of laboratory environments, leaving aside the broader socio-economic dynamics captured by our framework.[10]

Our interpretation of the term 'repertoire' owes much to research done on other areas of human activity, and particularly on the performance of music, acting, painting, and cooking. In science as in the arts and crafts, repertoires capture behaviors, skills, and abilities that are always enacted in specific spatio-temporal circumstances and indeed do not exist independently of their local manifestations, but which nonetheless can be analytically abstracted from their specific performances at any one point in time, and can thus provide a recipe for the assemblage of skills, concepts, instruments, materials, settings, strategies, procedures, and institutions required to perform.[11] As sociologists Robert R. Faulkner and Howard S. Becker (2009; see also Becker and Faulkner 2013) put it in their analysis of repertoires in jazz music, it is "important to not only know it [the items in the repertoire, e.g. the songs], but to know what to do with it, i.e. to enact it." We view this performative aspect of repertoires as critical, especially in comparison to philosophical work on styles of reasoning, which tends to ignore it in favor of aspects that are more easily specifiable without reference to skills and behaviors. For instance, both A.C. Crombie (1994) and Ian Hacking (1992, 2002) associate 'styles of reasoning' with conceptual and material tools and protocols, rather than with specific abilities and ways of proceeding; Otávio Bueno (2012) defends an

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[10] This feature of experimental systems is explicitly acknowledged by Rheinberger writing with Müller-Wille (2012) on their cultural take on the history of heredity, where they expand the scope of their analysis by introducing the notion of 'epistemic space.'

[11] We do not have space in this paper to explore the similarities (and differences) to the use of recipe in the context of repertoires and Marcel Boumans's use of the term with regard to models (1999), but this topic warrants additional exploration.

even narrower concept of 'styles of reasoning' as a pattern of inferential relations specific to a scientific subfield. Our views are closer to John Pickstone's account (2000) of 'ways of knowing,' which include an emphasis on historical and practical aspects of performance: repertoires may indeed be viewed as local arrangements through which different ways of knowing come together, and which, if re-enacted in a variety of situations in several groups in ways that make them resilient in the long term, may themselves become a specific way of knowing.[12]

3. Examples and Key Characteristics of Repertoires

Recent empirical work on experimental cultures and practices in the life sciences documents what we consider to be successful repertoires on the basis of their visibility, prestige and recognition, as well as the strategic advantage attached to their adoption by research groups, over the last fifty years.[13] For instance, consider model organism research. A small group of species, including the fruit fly *Drosophila melanogaster*, the nematode *Caenorhabditis elegans*, the zebrafish *Danio rerio*, the budding yeast *Saccharomyces cerevisiae,* and the weed *Arabidopsis thaliana,* has dominated experimental work in molecular biology over recent decades. This dominance has not arisen because they constitute the best biological materials with

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[12] Another body of literature that bears significant parallels to our views is that on regimes within and beyond techno-scientific communities (Foucault 1970; Pestre 2003; Cambrosio, Keating, and Nelson. 2014). The relation between repertoires and regimes deserves more attention than we can devote to it here, and we shall address it in future work.

[13] The examples that follow are necessarily compressed in historical and other terms for purposes of this paper.

which to work in any objective sense, nor because other species are too difficult or unwieldy for experimental work (as Dietrich, Chen, and Ankeny 2014 demonstrates, research on non-model organisms continues to flourish), though many model organism species were initially adopted because of their tractability, ease of storage, and low costs of production and maintenance. Instead, these species have risen to prominence thanks to their proponents' efforts to portray them as 'obligatory passage points' (Callon 1986) for multidisciplinary collaboration across biological subfields. The proponents of the key model organisms were able to convince colleagues, peers, and large-scale governmental funders that repeated use of and reference to the same organism provides critical opportunities for sharing knowledge, materials and technologies across biological disciplines and research groups, and indeed constituted an anchor around which entire research communities could be built (Ankeny and Leonelli 2011). Thus, thousands of researchers from a variety of locations across the globe got involved in enacting and developing a repertoire that included the conceptualisation of specific organisms as 'model systems', with related theoretical assumptions and commitments around which research questions to pursue; strategies to acquire blue-skies funding support particularly from the US and UK governments, which enabled research to develop within relatively well-resourced conditions; specific norms and behaviors, and particularly an ethos of sharing data and techniques prior to publication, which were attractive to like-minded researchers and contributed to the continuity of the research efforts and their abilities to accrete over time; the standardization and centralization of the production, use, and dissemination of specimens in stock centers; and the establishment of databases to gather both published and unpublished data in a standardized manner. These components may be disparate, but they are tightly interconnected, and could not function effectively without each other; for instance, norms around sharing would not be sustainable in the absence of governmental support that enables individuals and groups to disseminate results and materials efficiently without having these processes distract from the doing of research. Significantly, the hard-won ability of researchers to effectively align these components gave rise to a wealth of theoretical and experimental results, as well as ways of labeling and organizing those results for future consultation for a variety of other research purposes, which shaped biologists' actual understanding of these organisms (Leonelli and Ankeny 2012).

Another, more recent case of a repertoire within the life sciences can be found in the rise of microbiome projects. The idea of the 'microbiome' arose in the early 2000s with the Human Microbiome Project and the Gut Microbiome Project (Huss 2014). This concept was rapidly adopted within diverse initiatives such as the Earth Microbiome Project, exploring variation of ecosystem niche structures at biogeochemical scales; the American Gut project, which uses crowdsourcing to collect data about microbes populating the guts of American citizens; the Soil Microbiome, investigating microbial diversity of prairie soils; the Home Microbiome Study, analyzing associations between the microbes of families and their homes; and the Hospital Microbiome, comparing microbes in hospital environments during and after construction. These involve highly multidisciplinary teams distributed across several geographical locations, common strategies to attract governmental funding, efforts to engage in international standardization efforts related to the data, technologies, and software, a commitment to conceptualizing organisms and ecosystems as multispecies environments with unique microbial footprints, and a large-scale mode of operation, relying on vast samples of data acquired via metagenomic investigations of several microbial populations (so-called 'big data') and exploiting social media and crowdsourcing technologies to enhance their public profiles and attract volunteers in order to collect samples and help analyze results. Viewing knowledge about how to effectively align such disparate components as part of a repertoire highlights the motivations and advantages involved in developing and adopting this way of organizing and carrying out research. Scientists working on microbiome projects have discovered how effective use of social media, standardization efforts and open science discourse can reinforces their abilities to attract resources from diverse funding sources, which in turn affects the scope and directions of their research.

These two cases illustrate the importance of a repertoire in enabling coordinated research within a geographically distributed, multidisciplinary community, thus strongly affecting the knowledge produced therein. Focusing on repertoires highlights the ingenuity and labor involved in setting up and successfully managing collaborations among researchers based in different settings and equipped with widely differing disciplinary backgrounds and training. They also exemplify the conditions under which some such groups are able to endure beyond the completion of a specific project, without wedding their work to a particular subfield of biology, and thus retaining their multidisciplinary nature.[14] At the same time, these cases demonstrate the potential diversity in the lifespans of repertoires, with the microbiome example illustrating their power to grow and take hold across a wide range of research areas over relatively short periods of time, and the model organism example instantiating

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[14] For a discussion specifically focused on the longevity of communities which have repertoires, see Leonelli and Ankeny 2015; note that the focus in the current paper is different in that we explore repertoires as resilient, as well as analysing them in comparison to major theories of scientific change in detail.

growth of a repertoire over a relatively long timespan, which nonetheless resulted in a particularly resilient example.[15] Furthermore, these two repertoires exemplify the crucial role of strategies for obtaining funding and patronage, as well as the importance of communication and promotion about research to both peers and wider publics.[16]

4. Transferability and Variability

Perhaps most crucially, the two cases above illustrate how the establishment of a repertoire enables specific types of collaboration to become transferrable across research groupings, thus creating a well-tested recipe for how to organize research in a manner that is effective in terms of achieving certain goals, given particular environmental conditions. Resilience and transferability of repertoires come from the ways in which collaborations are organized, particularly with regard to their accommodation of multidisciplinary perspectives. Precisely because these collaborations are not strictly modular, it takes creativity and innovation to produce a model for how those with different disciplines and skills come together (for instance computer scientists, statisticians, biologists, and clinicians in the example below of clinical trials). Nancy Nersessian and Miles MacLeod have documented the ingenuity involved in creating multidisciplinary working environments in the context of specific

[15] As we discuss in more detail in the next section, these differences in lifespans raise interesting questions around the durability and longevity of specific communities in relation to their repertoires.

[16] Indeed, we contend that repertoires create 'publics' in a recursive way, as proposed by Kelty (2008) in relation to Open Software (which is arguably itself another example of a repertoire).

laboratories and projects, stressing the versatility of such social and scientific constructs through the idea of 'adaptive problem spaces,' in which different experts come together to tackle a common problem (Nersessian 2006; MacLeod and Nersessian 2013). The collaborative arrangements and behaviors devised within problem spaces do not always give rise to a repertoire, and may remain local and specific in the vast majority of cases. In contrast, our focus on repertoires draws attention to cases where the complex conceptual, social and material arrangement created in relation to one problem is recognized as useful elsewhere, and then is successfully instantiated beyond the original setting — enabling other researchers to use a readily available framework without having to 'reinvent the wheel.'

This type of transference is particularly useful in contemporary science, where scientific management involves numerous types of tasks, ranging from the choice of research questions, tools, and methods to decisions concerning dissemination, public engagement, and funding strategies; and many researchers look for ways to curtail time spent on what they view as logistical and administrative matters, so as to devote as much attention as possible to intellectual content and procedures. In this respect, repertoires function much like a franchising business model, where "a franchisor provides a licensed privilege to the franchisee to do business and offers assistance in organizing, training, merchandising, marketing and managing in return for a monetary consideration" (Small Business Encyclopedia 2015). A franchise model is flexible about what the relevant business may be—it may or may not include the production of goods, their distribution and marketing, and strategies for advertisement and consumption. What attracts investors, and is widely treated as valuable and thus sellable, is the specific way in which the business is established, organized, and enacted. Indeed, selling a franchise typically involves providing both resources and training (as well as detailed instructions) for how to deploy those resources, so that individuals who were not previously associated with the business in question can replicate it and manage it in new locations. Research repertoires function in a similar way, except insofar as the adoption of a repertoire typically does not involve monetary valuation or transaction, which makes the relationship between the creators and the users of repertoires much looser, less regimented, and thus more unstable than the licensing agreement between franchisor and franchisee.[17]

To underscore this idea, we briefly provide several additional examples of successful repertoires.[18] Within medicine, a well-documented case is the establishment of clinical trials as the most authoritative method for the production and validation of medical evidence. Peter Keating and Alberto Cambrosio (2012) have discussed clinical trials in oncology as a novel 'way of knowing,' distinct from the taxonomy of styles and practices identified by Crombie (1994), Hacking (1992, 2002), and Pickstone (2000) discussed above, and involving specific ways to enact assumptions around what constitutes health, treatment, and patient participation (see also Solomon 2015). Effectively operationalizing clinical trials, and making them transferrable across locations and clinical problem spaces, involves the development and alignment of institutional and scientific procedures, funding streams and related spaces

[17] The franchisor profits financially from the wide adoption of its business model, while there is no clear recognition attached to the creation of a repertoires in science, except for informal acknowledgment from peers and the advantages associated with being the first to establish it.

[18] To put philosophical points into relief, we have chosen well-known examples about which readers will be able to fill in historical and scientific details via existing literature.

(including industrial complexes), norms, and specific conceptualizations of what counts as medical knowledge. Most significantly, the entrenchment of this repertoire has paralleled the institutionalization of randomized controlled trials as the 'gold standard' for evidence-based medicine, which continues to rule pharmaceutical and other forms of medical research despite numerous critiques (e.g., Timmermans and Berg 2003; Cartwright 2007; Clarke et al 2014).

Within psychology, Freudian psychoanalysis exemplifies the establishment of specific techniques and theoretical frameworks for understanding and treating mental illness through the adoption and enactment of an ensemble of behaviors, physical arrangements (e.g., the chaise lounge, the positioning of the analyst with respect to the patient, and use of a silent room without distractions), and social relations between the analyst, other analysts, and patients and their families. As documented by historians (e.g., Schwarz 1999), although publication played an important role in the dissemination of his ideas, Sigmund Freud's attempts to promote his approach went well beyond his books. He was able to train capable pupils who then transferred the repertoire to new locales, including its norms and attitudes toward patients which are much less easy to formalize than other aspects of Freudian practice, and are taught through observation, mimicry, and practice. Of these behaviors perhaps the most familiar are Freud's efforts to train pupils to reflexively exploit the analyst's power position with respect to patients, and channel the sexual tensions thus created as part of therapy. This process involves not only conceptual analysis, but the enactment of the most socially repressed of all behaviors, which in turn requires a specific sensitivity and self-knowledge which is impossible to articulate through text: the behaviors must be performed. The relentless promotion and re-enactment of this repertoire was crucial to making Freudian psychoanalysis transferrable beyond

Vienna, and to its institutionalization in Britain and the United States in the 1950s and 1960s.

It is important to note that when transferring or adopting a repertoire from elsewhere, the goal often is not to reproduce the repertoire faithfully and *in toto*. Variations and local specificity of performance are not only admissible, but are expected and in some cases crucial to the successful enactment of a repertoire. To understand this, it is useful to consider again the analogy with the performance of jazz repertoires, where what matters is not meeting some (non-existent) immutable ideals of perfect performance, but instead giving a performance that is 'good enough' to be recognizable as part of the repertoire, while also being original enough to be worthwhile based on its own merits (see Becker and Faulkner 2013). Similarly, research repertoires need to remain identifiable, so as to retain their effectiveness and potential transferability, while also acquiring specific characteristics to be usable within the particular setting in which they are enacted. Thus each instantiation of a repertoire is necessarily subject to variation and change, as specific enactments of given behaviors and resources will yield different results, depending on the interpretations of the individuals involved and the local situation within which the repertoire is enacted.

Consider again the example of microbiomes: this repertoire became successful because it proved useful to attract funding and interest within and beyond the scientific world. For it to be extended to new areas, several components needed to be in place that would align with the characteristics and norms of this repertoire: for instance, researchers willing and able to implement the repertoire's strategies; unsolved questions of high interest to funders that could be tackled through the meta-genomic methods and technologies specific to the repertoires; and conceptual assumptions around how living systems can be investigated that would be compatible with those made within the repertoire, including whether certain kinds of generalizations can be reliably extracted from meta-genomic analysis. Thus implementing the repertoire helped scientists to mobilize and align these components effectively so as to produce a fruitful and well-funded environment for research. At the same time, each instantiation of the microbiome repertoire had to introduce something unique and new that would give reasons for funders to support a particular project as a source of original outputs. Thus while repertoire can be characterized and recognized at any point in time by reference to the components, commitments, and behaviors that recur across each of their instantiations, variations among those instantiations are required for a repertoire to be transferable, successful, and persistent beyond the situation within which it was originally developed – and the accumulation of variations through successive re-enactments constitutes the main mechanisms through which repertoires evolve and change over time.

5. Repertoires and Research Communities: A Complex Relation

A key set of questions concerns the relation between repertoires and research communities,[19] and in particular whether communities are defined by the adoption of a repertoire in the first place, and whether it is possible for the same community to enact different repertoires at the same time. For the purposes of our present argument, we define communities very broadly as groups of researchers that collaborate towards

[19] There is much more to be said about the relationships between repertoires and communities, including discussion of relevant scholarship in the social sciences and history and particularly of literature on group identity and field/discipline formation. This is beyond the scope of this paper.

a common goal for longer than required for the completion of one specific research project, and are therefore relatively stable and coherent. While communities can be defined and established in a variety of ways within science, we contend that a popular and effective way to form and stabilize a community is the development or the adoption of a repertoire. We also defend the idea that the same community can, and indeed often does, simultaneously utilize more than one repertoire. In order to explore this claim, it is critical to note that most of the examples provided so far in this paper emerged when researchers consciously put concerns around the development and maintenance of a particular repertoire at the center of their science. Researchers involved in setting up the repertoires discussed above developed their strategies vocally and self-consciously, often by borrowing ideas from other successful initiatives and with a strong mandate to expand and transmit them. For instance, many of the architects of modern model organism communities, particularly Chris and Shauna Sommerville in the case of Arabidopsis, articulated their vision for how to guarantee longevity for their communities at the very start of their involvement. They effectively outlined the ingredients required to build a repertoire, in part borrowing from the repertoire that already existed in the *Caenorhabditis elegans* community (Leonelli 2007). Finding ways to realize this vision required the joint efforts of two generations of Arabidopsis researchers, so that the repertoire came to have significant longevity and to be adopted by other communities.

There also are instances where repertoires remain an implicit part of everyday scientific work, particularly as some elements of successful repertoires can become so thoroughly entrenched in research practices so as to become invisible. This point is underscored by philosophical scholarship on material, conceptual, and social scaffolding in knowledge production, which explores the mechanisms through which concepts, approaches, and tools become embedded within emerging communities, and highlights the significance of such scaffolds disappearing from view or being removed altogether once a given set of practices is in place (Wimsatt and Griesemer 2007; Caporeal, Wimsatt, and Griesemer ed. 2013). In line with these findings, some components of a repertoire are only articulated during training, and sometimes not even then. For instance, the norms associated with sharing if data and probes in model organism communities are now so strongly entrenched that they are simply copied across generations usually without being explicitly discussed or contested. In particular, the practice of depositing genetic sequences in public databases as soon as they are generated began to take hold in the late 1980s and was enshrined formally in the 'Bermuda Principles' in the 1990s (Contreras 2011), after which it became a background assumption for those doing biological research, particularly since it became evident that there was much to be gained from these behaviors (and not much to lose for most). A more familiar example is the 'black-boxing' of theoretical assumptions (a phenomenon that Kuhn [1962] interpreted as grounds for conceptual incommensurability among paradigms, and Wimsatt [2007] discussed as a form of 'generative entrenchment') that can occur when those assumptions become embedded within the performance of a repertoire. For instance, using model organism databases makes biologists subscribe to theoretical assumptions embedded within technology-driven classificatory practices, often without knowledge about or explicit endorsement of them (Leonelli 2012). More generally, technology is a key component of platforms that tends to become invisible as soon as the skills required to use them can be taken for granted within a given community, an insight amply illustrated by Keating and Cambrosio's work (2003) on biomedical platforms.

The repertoires that researchers adopt most consciously are the ones that are easiest for philosophers to document and study, as evidence is readily available from historical and scientific literature. Repertoires that are adopted tacitly, without explicit recognition by the researchers who employ them, are more difficult to identify.[20] Their visibility may increase depending on how they intersect with other repertoires used by the same community at specific points in time, particularly in cases of perceived conflicts between norms and behaviors associated with different repertoires. Consider the repertoire utilized by model organism communities in terms of its evolution over time. This work began in the 1970s with a strong emphasis on stock centers, because access to standardized materials was critical to making the repertoire viable. Emphasis shifted in the 1980s and 1990s to data sharing and coordination of efforts. This change was partly due to the existence of reliable stocks that could be accessed worldwide and relatively easily, and partly determined by the intersection of model organism research with another repertoire, that of genetic sequencing, which involved commitment to high-throughput technologies and a focus on a few key strains as research materials which were considered sufficient to unravel questions concerning the relation between different molecular components. This move went relatively unchallenged (despite critiques, e.g. Bolker 1995) until the last decade, when many researchers became interested in the environmental variability of these organisms, whose study requires comparative field sampling and application of genetic tools to study organismal forms which occur both within and outside of the laboratory (e.g., Sterken et al. 2015). In this new landscape, the repertoire of genetic

[20] Here philosophers could benefit by collaborating with sociologists and historians of science whose data collection techniques are more likely to reveal such processes and patterns.

sequencing and its conceptualization of organisms acquired greater visibility by being explicitly questioned.

Another example is provided by the recent intersection between model organism research and the emergent repertoire of synthetic biology, which involves a large amount of standardization, relatively little attention to organisms as wholes (in favor of more modular approaches), and funding in the form of private–public partnerships. In some of these cases, researchers who formerly relied on long-term governmental funding have been forced to consider commitments and practices relating to a different intellectual property regime that includes patenting, down streaming, and copyright issues. This situation has generated conflicts between repertoires, for instance where researchers wish to publish data as soon as it is produced, and yet do not know whether data publication would be acceptable to their private sponsors.[21] Researchers involved in both repertoires are no longer clear about which expectations around ownership and dissemination of results they should conform, how, and why.

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[21] See Levin and Leonelli (2016). In relation to synthetic biology, it is important to stress that this label covers a heterogeneous variety of methods, concepts and aims, and thus can result in different scientific approaches (e.g. O'Malley 2009). At the same time, there are strong institutional and financial incentives (in the form of favorable governmental policies, preferential funding streams, university-based hiring procedures and organization of research directions, and so forth) for practitioners to identify with this label and coordinate their research efforts so as to fit governmental agendas. Largely due to these 'external' incentives, synthetic biology arguably constitutes an identifiable repertoire, albeit one characterized by a high level of pluralism in the methods and conceptual perspectives adopted by researchers.

These examples illustrate how different elements acquire prominence at different points in the repertoire's life cycle; what becomes visible and when may depend on other repertoires at play in the same community. Thus the same community of scientists can employ a variety of repertoires at any single point in time (in line with Fleck's views and contra Kuhn's paradigms), in ways that can be more (or less) self-aware and reflexive. There is often no simple, one-to-one relation between repertoires and communities: some communities use multiple repertoires at the same time, a particular repertoire can be utilized simultaneously by more than one community, and some research communities lack repertoires altogether, as we discuss in the next section.

6. Alignment

Communities with successful repertoires share the ability to align the components of their work, including technologies, research goals, and materials, with broader components over which they have much less control, such as funding structures, the moral economy within the community and more broadly the scientific field, and social and political structures. Keating and Cambrosio (2003) stress the importance of (and difficulties in achieving) alignments between different platforms[22] which co-exist within the same epistemic spaces. Their preoccupation with explaining this phenomenon is similar to ours: far from providing an epistemic foundation for research practices, platforms are pragmatic tools which support the organization and management of such practices, and are successful insofar as they determine "what

[22] They define platforms as "the intersections of distinctive arrangements of instruments and programs that seek to articulate biological and population data with diagnostic and prognostic singularities" (7).

works best for a given purpose, given a necessarily limited amount of information, opportunities and resources" (28). Similarly, to understand what constitutes a successful repertoire, it is necessary to investigate how they come to co-ordinate a variety of diverse components— typically including several platforms—in ways that enable them to thrive and become embedded as essential conditions for particular kinds of research practice.

For such alignments to be effective, participants who perform a shared repertoire need to make assumptions about who the other relevant participants are, what they do (or do not) know, and what they can (or cannot) do. Hence participants need to share knowledge about which actors, knowledge, settings, and materials are relevant to the performance of their target activity, as well having access to those elements. They also need to possess skills relevant to using that knowledge and related materials to create the desired performance (skills which may of course diverge significantly person to person, depending on each individual's role). Finally, they need to know which role(s) they are expected to play within the repertoire, and have expectations as to what others can and cannot be expected to do (think for instance of the tacit assumptions around data sharing discussed above). It is important for participants in repertoires to know the boundaries and constraints attached to the settings in which they operate: some of the conditions in which repertoires may be created simply cannot be changed, as they do not depend on any potential actions of individuals or communities involved, but on much broader dynamics and situations (such as national policies, economic climate, financial resources at hand, and so on).

To understand the concept of alignment within repertoires, it is useful to consider examples where (contrary to those above) repertoires are not resilient, long-lived, or replicated by different communities. Research with the mouse in the context of the non-human sequencing programs in the Human Genome Project presents a clear case of scientists coming together to meet short-term goals, and attempting to build on their temporary alliance to foster longer-term collaborations, but ultimately failing to establish a long-lived repertoire. The mouse and those who work on it have made critical contributions to a range of biomedical efforts over the course of the 20th century (Rader 2004; Lewis et al. 2013).[23] While research in other organism-based communities took place mostly through blue-skies public funding, the majority of research on the mouse over the last three decades took place in private facilities, including pharmaceutical testing and clinically-related endeavors subject to stringent regimes of regulation and intellectual property (Davies 2013). Despite several attempts, these constraints made it impossible for researchers to establish common and freely accessible resources characteristic of other model organism research, such as centralized stock centers and databases. Hence transactions associated with strains and other resources are typically costly, thus limiting access to those who have the requisite finances. Undoubtedly some components of the repertoire associated with model organism work and with molecular biology as described above were present, including the concept of a 'model organism' and use of certain technologies (particularly genomic sequencing), but alignment did not occur between these components and others, and thus mouse researchers did not produce shared practices, aims, infrastructures, institutions, financial resources, and norms that could serve to

[23] It also is likely that there was a shared repertoire among those who did early immunological work (see Rader 2004), though we cannot pursue those details here; we are grateful to Scott Gilbert for stressing this point.

co-ordinate these disparate groups.[24] This lack of alignment continues to affect the knowledge produced by this community, with researchers focusing largely on strain-specific molecular mechanisms and complaining that the lack of co-ordination makes it difficult to tackle comparative and integrative questions.[25]

Hence, failure to establish or reproduce a repertoire typically results from a lack of alignment and/or knowledge about the components of a repertoire as well as about the accompanying boundaries and constraints. Alignment is not only difficult to generate, but also to maintain in the long-term, particularly when repertories are transferred to different situations. Indeed, repertoires are not easy to export, and their travelling abilities are often limited as they are resoundingly local.[26] Consider for instance research with super-colliders in physics. This case provides an excellent example of a repertoire that goes well beyond the focal technology (though of course the

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[24] It may well be that they established a 'platform' in the sense intended by Keating and Cambrosio (2003) (we are grateful to Chris DiTeresi for this suggestion) but a detailed comparison between platforms and repertoires is beyond the scope of this paper.

[25] Another example of lack of alignment leading to the failure to establish a long-lived repertoire can be found in Knorr-Cetina (1999, 234ff.), who noted the 'impossibility of cooperation' inherent in molecular biology laboratories that she observed in the 1980s. She attributes this to the complexities of the available technologies and the dominance of individualistic norms in the broader field, a situation that we would argue changed with the advent of large-scale sequencing projects in the 1990s (Hilgartner 2013).

[26] For discussions on related issues about 'travelling facts,' see Howlett and Morgan ed. (2010).

technologies and accompanying experimental settings are critical to the scientific practices of the community), as the success of this type of work also hinges on methods of communication and promotion within and beyond the research community, as well as on associated governmental policies (Traweek 1988). The discovery of the Higgs boson was due to CERN scientists' abilities to align their research practices with funding and institutional requirements, which made it possible for them to collaborate effectively. By contrast, the attempted use of this repertoire in the United States exemplifies a failure in the alignment of the technology, aims, public discourse, funding, and governmental policies that resulted in a dramatic loss of research capabilities and a shift of direction for the field as a whole.[27]

Due to the creation of various alignments, repertoires also produce specific material, theoretical, and social commitments, which can serve as constraints on future innovation. For instance in contemporary molecular biology, those constructing data infrastructures typically attempt to incorporate a range of existing repertoires from the start, because they want these infrastructures to be successfully used by a variety of researchers including those with differing epistemic commitments (Leonelli 2013). At the same time, the instruments used for data production (such as mass spectrometers, microarray chips, and so on) are mass-produced by companies to focus on a narrow range of data types, which in turn greatly reduces the sources of evidence generated and used by researchers (which Ulrich Krohs [2012] dubs 'convenience experimentation'). This situation can have negative consequences as the resulting data

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[27] This example also helps to illustrate another key characteristic of repertoires: no one component of the repertoire is central, primary, or fundamental (e.g., methods or techniques, technologies, and so on), in contrast to Lakatos's hard core in his account (1970) of scientific change.

can flood the research landscape in a disproportionate manner, sometimes without quality checks, which in turn creates incentives to keep exploring these data rather than creating novel data in response to novel research questions, thus potentially curtailing scientific innovation.

Given the potential disadvantages involved in adopting a repertoire, it is important to note that not having a repertoire, or failing to create one, does not in principle compromise a community's ability to produce knowledge (though it certainly can affect it in practice, as in the cases of research in low-resourced environments such as sub-Saharan research biomedical labs, as analysed by Bezuidenhout et al. 2016 and Leonelli under review). What it unavoidably affects is the type of knowledge that a community is able to produce, which can have both negative and positive implications. The failure to establish a particular type of repertoire in mouse research and in U.S. particle physics could have stimulated significant discoveries; the history of science is full of cases where communities produce innovative results by resisting the urge to establish a repertoire, or even challenging existing repertoires (e.g., Chang 2012; Harman and Dietrich ed. 2013). Thus repertoires are not necessary to the pursuit of scientific research and do not constitute an absolute ideal toward which all scientific communities should strive: they create blind spots and forms of path dependence that can be fruitful or problematic, depending on the situation and point of view.

7. Conclusions

Using the framework of 'repertoires' allows exploration of aspects of scientific practice which have been largely overlooked in philosophical accounts, including economic structures, politics, norms, and other social and performative features, as well as applications of research. These aspects are not typically discussed within scientific publications, which partly explains why they have been less accessible to philosophers despite having been amply documented and analyzed by historians and sociologists of science. Repertoires permit us to investigate the interrelation between these parts of scientific research and other components of practice, thus facilitating a more comprehensive view of the drivers of scientific change in at least three ways:

- by facilitating a better understanding of the relationship between individual contributions and collective practices and norms;
- by forcing philosophers to consider the research practices and behaviors associated with policy, funding, public relations, marketing, and institutions—including how and when these factors do (or do not) align—thus highlighting the significance of political economy for any account of the epistemology of scientific practice;
- by encouraging a critical assessment of what 'success' in science involves, how it is achieved and how evaluations of success and failure can and do shift over time; and
- by broadening our view of what 'counts' as scientific work to include the contributions of science administrators, technicians, funders, and other non-scientists whose skills and expertise contribute significantly to the enactment of research repertoires.[28]

'Repertoire' is both a descriptive and an explanatory notion that can be used to explore how collaborations work and why particular research communities prove more long-lived and durable than others. The repertoires framework requires that the

[28] This perspective has implications for various research practices including credit attribution, and supports a highly distributed model of how science is done.

analysis of collaborations be placed at the center of any general philosophical account of scientific change and the nature of research communities. It is complementary to many discussions in philosophy of science as detailed above, fosters exploration of basic, applied, and translational forms of scientific practice, and may extend beyond the realm of science to analyses of the evolution of cultural practices more generally. As we have shown, repertoires are particularly useful when exploring the complex multidisciplinary assemblages that characterize much of contemporary scientific practice, but the notion is also applicable to the history of science, particularly to research that is not grounded in any one disciplinary perspective and involves significant collaborations.

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