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Invention through Bricolage: Epistemic Engineering in Scientific Communities

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Abstract: It is widely recognised that knowledge accumulation is an important aspect of scientific communities. In this essay, drawing on a range of material from theoretical biology and behavioural science, I discuss a particular aspect of the intergenerational nature of human communities – "virtual collaboration" (Tomasello 1999) – and how it can lead to epistemic progress without any explicit intentional creativity (Henrich 2016). My aim in this paper is to make this work relevant to theorists working on the social structures of science so that these processes can be utilised and optimised in scientific communities.

Keywords: Epistemic engineering; thought styles; Philip Kitcher; virtual collaboration; cumulative culture; philosophy of science; scientific communities; cultural niche; interdisciplinarity; Joseph Henrich

> *How do we best design social institutions for the advancement of learning?*
> *The philosophers have ignored the social structure of science.*
> *The point, however, is to change it.*
> (Kitcher 1990 : 22)

1. Introduction

A common problematic trait in some popular accounts of the history of science is to overly focus on the individuals. Einstein, Darwin, and Galileo are household names and exceptional individuals worthy of attention. But this view tends to overlook the importance of the social institutions that create the epistemic environment in which these individuals operate; and the conditions for how epistemic progress can be made. As Fleck remarked, without this proper context, one's analysis will ultimately

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be fruitless (1979 : 21). In this paper, I elucidate features of the intergenerational structure of scientific communities which have been underexplored: *viz.* the capacity of scientists to cooperate intergenerationally to achieve epistemic progress without there being any explicit intentional creativity (Henrich 2016). Building on an observation by Tomasello (1999) I shall term this "virtual collaboration". Additionally, I outline a range of tools from theoretical biology and behavioural science that can make features of intergenerational epistemic work clearer so that they can be properly explored and utilised. My aim in this paper is to introduce novel sets of experimental data and concepts into the debates about how to structure scientific communities in order to optimise cognitive diversity.

The paper is structured as follows: in the next section I briefly distinguish a range of important intra- and inter-generational factors discussed by other theorists. This then provides us with the necessary background to discuss how intergenerational 'creativity without intention' can take place. In the final section of the paper I speculate on how this general fact about human communities might be utilised for scientific progress.

2. Untangling intergenerational factors

Knowledge accumulation is widely recognised as a major feature of scientific communities. There are various important aspects of this that need to be outlined before I can discuss the notion of virtual collaboration. Firstly, we need to distinguish between differing temporal aspects of a community of inquiry: what I shall refer to as synchronic and diachronic. Much of the philosophical and sociological discussion of scientific communities focuses on a synchronic temporal region. I.e. they examine the structure of the community – its institutions and practices – in a contemporary time-slice or how it was at some historical epoch. For instance, discussions about the roles of ridicule and other social factors and how these impact group decision-making and collaboration often focus on a particular group over a short period of time (Sunstein 2005; and see D'Agostino 2008 for an overview). In contrast, we can also consider diachronic aspects – how a particular community of enquiry is structured over an extended period of historical time. My focus is on this latter aspect.

A second distinction is between social and epistemic features of this diachronic temporal scale. From a social perspective we can consider how a community of inquiry inculcates new members through their acquisition of a range of social practices and relevant bodies of knowledge for the specific field (see Menary & Gillett 2017 : 78-79). But there is also an epistemic element as well which relates to the transmission of information from one generation to the next. However, this distinction is not clear cut for a number of reasons. For instance, the developmental trajectories of specific agents into the practices of a particular scientific practice involve the extensive acquisition of practices, techniques, and general know-how related to the tools and theories of a particular scientific field (Nersessian 2005). As such, the developmental trajectory of a young scientist involves being taught the tools for navigating certain epistemic matters. We can adopt terminology from theoretical biology to label this a "developmental niche" (Flynn et al 2013). This is a structured or "seeded" learning environment whereby the activities of the previous generation enhance the learning pathways of novices through what Sterelny calls "hybrid learning" (2012). Hybrid learning involves a mixture of processes including direct teaching, but also the creation of a learning environment which improves the trial-and-error learning of the novice. Vygotsky (1978 : 84-91) referred to this as the "zone of proximal development"; whereby a novice's capacities in a particular task domain are improved by the presence of an expert who can steer the efforts of a novice so that they are more successful. For instance, in the complex procedures involved in interpreting fMRI data, Alač & Hutchins (2005) note that the expert scaffolds much of the interpretative work done by the novice. This often involves the creation of intermediary and temporary representational devices to facilitate this, such as diagrams and visual aids.

But the intersection of social and epistemic aspects in the diachronic structure of communities of inquiry is not just limited to the developmental niche. New members of the scientific community are inculcated into the practices, techniques, and knowledge of that particular community. This is an enculturating factor on the cognitive processes of new members, which will include certain kinds of theoretical vocabularies and "thought styles" (Fleck 1979). Thought styles here refers to modes and styles of thinking that are prevalent in specific communities that structure how the domain space is apprehended. For instance, the geographic information sciences operate with a digital numerical and discrete conception of space (Hutchins 1995). The structure of these enculturating processes is shaped by the activities of the previous generation and have long-lasting effects. Indeed, the activity of one generation alters the problem spaces of the next generation. Sterelny (2003 : 148) refers to this as "epistemic engineering". To return to the example of the geographic information sciences, contemporary navigational and map-making problems take place in a computational problem space that has been radically reshaped by the empirical and theoretical work of multiple generations of geographers (Bray 2014; Hutchins 1995; Snyder 1987). This highlights a distinctive aspect about human social groups – "cumulative culture" – whereby novel features of a skill, technique, or artefact are successfully transmitted from one generation to another in a reliable manner. Tomasello (1999) has identified cumulative culture in general as a distinctive trait of our species[1]. Here we are particularly concerned with how one generation is able to alter the epistemic problem spaces in a downstream manner so that future generations can build from these starting points.

Arguably, scientific communities are the most rarefied form of this distinctly human trait for the accumulation of knowledge and technologies because institutional structures facilitate the critiquing and the improvement of practices, techniques, and theories (e.g. such diverse views as Ladyman & Ross' (2007) ontic structural realism and Stanford's (2016) integrative naturalism agree on this point). However, whilst some might see this as an overly obvious point, others will argue, *à la* Kuhn (1970), that a notable feature of scientific communities is their occasional habit of disregarding the work of previous generations and abandoning it in favour of alternative views. To this I would suggest that even with the most extreme reading of "Kuhnian losses" in a paradigm shift it is arguable that there is still some carry over of some of the material and epistemic achievements of previous generations (even if this cannot be identified in a non-*ad hoc* manner). Indeed, even in the weakest possible sense we can argue that the problem space in which a new paradigm is put forward involves an epistemic environment that has been extensively engineered through the perceived failures, inexplicable empirical findings, and other conceptual issues of the previous paradigm. For instance, in the science of navigation the introduction in the Twelfth century of the magnetic compass in Europe

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[1] This point is made with the caveat that there is some recent evidence of cumulative culture in chimpanzees, orcas, pigeons, and baboons (Vale et al 2017). But this does not greatly undermine Tomasello's point because the accumulative aspects in other species are of a limited nature – involving very few cultural factors. In contrast, cumulative culture is widespread and abundant in humans.

(Hutchins 1995 : 93)[2] not only radically reshaped how people orientated in space (from the East-West axis of the passage of the sun to a North-South axis); it also reshaped how people thought about and conceived of space at a deeper level. As Hutchins notes, many advanced modern navigators are taught to "think like a compass" (141). And it also allowed for a much more accurate and discreet measurement of angles in space (whilst operating alongside a range of other tools and techniques)[3]. But despite this, much of the traditional problem space of European navigation remained – despite being obsolete or anachronistic in some cases.

A related issue here of the intergenerational structure of scientific communities is the extent to which social issues can impact on epistemic matters to prevent the advancement of new ideas and theories. It is often commented that new and superior theories do not win the day purely on epistemic grounds – a point famously contested by Feyerabend (1975). I think one of the main strengths of Kitcher's work (1990, 1993, 1998) is the recognition that we must take these social factors into consideration when considering epistemic matters. Viz. that we should not treat scientific communities as populated by 'epistemic saints' motivated only by the truth; and that epistemic and non-epistemic factors can come together to create a "valuable cognitive diversity" (1993 : 306).

On the other hand, it is notable that the problem of failing to consider viable alternative hypotheses – what Stanford (2015) calls the problem of "unconceived alternatives" – is exacerbated by the developmental aspect of scientific communities that we have been discussing because they can lead to a fostering of certain conservative elements. Such a danger was noted by Max Planck who once remarked that scientific progress is not made through truth beating out falsity but because the opponents of an idea eventually die. Recent work by Azoulay and colleagues (2015) offers some empirical evidence to support this claim. They examined the publication histories of multiple fields before and the after the death of 452 eminent scientists and found that the publication rates of non-collaborators of the 'star scientists' in these fields increased in a dramatic respect to collaborators (whose publication rates went downwards). Empirical evidence supporting what has come to be known as "Planck's Principle" can be placed alongside a wide range of other social studies and theoretical models which point to the dangers and complications of social factors on epistemic matters (see D'Agostino 2008 for an overview). These should not be trivialised and indeed must be explored so that they can be mitigated or channelled.

This instance of epistemic dysfunction occurs because of the intergenerational structure of scientific communities. However, conservatism in scientific communities is not necessarily a merely negative aspect. Kuhn (1977) recognised that conservative elements within a community of inquirers are necessary for binding that community together and offsetting the innovators who try to drag a community in multiple directions across the "epistemic landscape". He labelled this balance the "essential tension". Recent modelling work offers support for this view by suggesting that diversity of opinion on epistemic matters needs to be temporary to prevent the splintering of the community; and that this fragmenting of the community leads to a decline in epistemic progress (Bailetti et al 2015; Zollman 2010). Excellent work by D'Agostino (2008) has "naturalised" the essential tension by collating the relevant research in the various social and behavioural sciences which relate to

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[2] The use of magnetic compasses came much earlier in China, perhaps as early as 200BCE.

[3] See Levinson (2003) for details about the various ways that people think about space – varying from egocentric to allocentric depending on primary linguistic terms. Also see Hutchins (1995) for a prolonged discussion of the different cultural niches and representational schemas for conceiving of space – analogue and approximate or digital and discreet.

conservative elements in collaborative epistemic settings. For instance, heuristics, biases, and metaphors (e.g. features of a thought style) can have a serious impact not only on what kinds of theories are considered but also who is granted epistemic warrant in a community.

D'Agostino (2008) notes that it is important to consider the social and affective settings of a community of enquiry: one with a negative affective valence will reduce the chances of diverse ideas being voiced within the community. For instance, the phenomena of "ridicule" (Sunstein 2005) can have a serious impact on the extent to which agents feel they can put forward suggestions in a group decision-making situation (also see Fricker 2007 who points out epistemic dysfunctions resulting from prejudicial stereotypes – what she terms "epistemic injustice"). D'Agostino also discusses the positive impacts of social factors in well-structured settings. For instance, "assembly bonus effects" – whereby a group is able to outperform the potential of its best member (Collins & Guetzkow 1964 : 58-60) – have been observed in the (in)famous Wason selection task. Individual performance on this task has a 10% success rate, but group performance is at a much higher 80% – Mercier & Sperber (2011 : 61-62) contend that this is because this test design reveals that human agents have a preference for confirmation bias. In this task setting, group work can counteract what is usually a negative individual trait because we are better at criticising others rather than ourselves; as such, it is collectively beneficial (also see Smart 2017). In general, D'Agostino (2008) notes that the structure of the problem space is crucial for whether it facilitates or inhibits assembly bonus effects. Given that scientific problem-solving has increasingly necessitated collaboration (Andersen 2016), it is crucial to explore what types of problem-situations and what kinds of group structure leads to either "collaborative facilitation" or "collaborative inhibition"[4].

This brief overview shows that both the positive and the negative factors at the synchronic temporal level and the negative aspects of diachronic temporal dimension are being considered both theoretically and empirically in the literature. My aim in the remainder of this essay is to supplement these discussions by outlining an important positive aspect of the diachronic structure of scientific communities which I think has been overlooked: what I shall call, using a phrase adapted from Tomasello's work (1999), "virtual collaboration".

3. Virtual Collaboration

In the previous section I outlined theoretical and empirical work that explores the interplay of social and epistemic factors across both synchronic and diachronic temporal domains which impacts on epistemic progress both negatively and positively. In this section my aim is to supplement this work by discussing recent work in theoretical biology and the behavioural sciences by Henrich and colleagues (Henrich 2016; Muthukrishna et al 2014). This work has shown that epistemic engineering, and the kinds of bricolage that occurs in the transfer of ideas and material across generations, can lead to epistemic progress without requiring a single moment of intentional genius. I think that this is an underappreciated point in science and technology studies. I will now outline Henrich and colleagues' views and findings before showing how this work applies to scientific communities. My aim is to make

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[4] Terms taken from Barnier et al (2008).

this work more widely understood in debates about the structure of scientific communities so that they can be restructured to make the most of this general feature of our species.

Recent debates in evolutionary psychology have concerned the role and importance of cultural inheritance to our species' success: Boyd, Richerson and Henrich point out that we inhabit an incredibly large area of the planet in a wide range of diverse ecosystems – more so than any other terrestrial invertebrate species (2011 : 10918). The traditional explanation for this success claimed that it is based on our superior general intelligence and capacity for problem solving (e.g. Pinker 2010). On this older evolutionary psychology account, these capacities are specifically genetically endowed; culture and social learning are mere add-ons or late additions. In contrast, Henrich has recently argued that this view is outdated and fails to acknowledge that cultural evolution has been the "central force" driving human genetic evolution for the last few hundred thousand years (2016 : 315-316)[5]. Against the older view in evolutionary psychology, Boyd and colleagues (2011) present two sets of evidence from what they refer to as "natural experiments" from the historical record: [1] lost European explorers; and [2] the loss of technology and practices in small isolated populations. They go on to claim that being able to survive in a wide range of hostile environments is dependent on our cultural niche and how knowledge can be accumulated across generations. Not even the smartest of us, Boyd and colleagues argue, could learn to live in a *de novo* environment through individual learning. This is a point that they think Pinker and others have misunderstood. Instead, "[w]e owe our success to our uniquely developed ability to learn from others" so as to tackle cognitive tasks utilising cognitive achievements "…that are too complex for any single individual to invent during their lifetime" (2011 : 10918).

During the period of colonial expansion and exploration, there are numerous cases in the historical record in which European explorers ended up stranded in a novel environment, fail to adapt to the local conditions, and subsequently die (see Henrich 2016 : ch3). In many of these cases the Europeans died in close proximity to an indigenous population who were flourishing in the very same environment. Boyd and colleagues give the case of the Franklin's expedition of 1845–1846 who perished from starvation and scurvy whilst seeking the Northwest Passage near the Artic (2011 : 10920). This is a particularly interesting case because approximately fifty years later Roald Amundsen spent two winters in the same region and became the first European to successfully traverse the Northwest Passage. The key difference was that he sought out and learnt from the indigenous population – adopting their tools and techniques for surviving in an inhospitable environment (Henrich 2016 : 26). Another example is the ill-fated Willis and Burke expedition in 1860 into the Australian outback of the Northern Territory. Their provisions were exhausted too quickly and they were only able to survive by the good graces of the indigenous population who gave them gifts of food including a cake made of a local plant product called nardoo (*Marsilea drummondii*). Willis and Burke sought out the plant by themselves and attempted to live off the crop, but unbeknownst to them nardoo is toxic unless processed properly, and this contributed to their deaths (Henrich 2016 : 27-30).

In a second set of natural experiments Boyd and colleagues (2011) outline cases were a small isolated local population lose sets of sophisticated tools and practices. Perhaps the most famous case

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[5] Also see Laland and colleagues (2010) for a recent review of this evidence, which interestingly shows that genetic evolutionary changes have been accelerating in the last ten thousand years.

is of indigenous Tasmanians who were separated from mainland Australia approximately 12,000 years ago when the sea levels rose. In this period of isolation, the Tasmanians began to lose complex tools. In the archaeological record it can be seen that their watercraft became simple and inefficient; their clothing became less complex; and their tool kits became much simpler – being limited to only 24 items in comparison with their contemporaries across the Bass Strait in Victoria who had a toolkit of hundreds of specialised tools (see Henrich 2016 : 220-222 for details). Another more recent example relates to a tribe of Inuit in Northwest Greenland who were severely hit with a plague in approximately 1820 (Boyd et al 2011 : 10920). All the elders of the tribe were killed along with the complete loss of cultural knowledge for how to make a range of important technologies and the associated skills for how to use them (e.g. kayaks). For the next few decades the tribe struggled by, diminishing in population, until they were discovered by another tribe who re-taught them the equivalent skills and techniques to those which they had lost. There are many more examples of this in the historical record.

We can take these two sets of natural experiments as an existence proof that it takes more than pure intelligence to make it in a novel environment. Instead it is our prosocial nature, and aptitude for social learning, that are really important. Henrich captures the central issue here by presenting it as a dichotomy in a thought experiment (2016 : 214-215). He imagines two prehuman communities composed of homogeneous populations: *Geniuses* and *Butterflies*. The geniuses are very inventive and create many new innovations but they are not very social and so are unlikely to pass them on to their conspecifics. In contrast, the butterflies are not smart but are incredibly social. Henrich's point is that even though the butterflies are far inferior in terms of intellect compared to the geniuses, they are much more likely to retain any innovations that they do stumble across. Whilst the genius population might generate far more innovations these are not retained or communicated intergenerationally because they are not social enough, and do not effectively share their knowledge. Thus, any innovations are lost. One might respond to this thought experiment that it is rather trite and does not really prove any point except that some degree of communication is necessary[6]. But recently an interesting series of lab-based experiments have explored Henrich's claim that prosociality is the key ingredient to our species' success (Derex et al 2013; Muthukrishna et al 2014). I now outline these before turning to their implications for scientific communities.

In two experiments by Muthukrishna and colleagues (2014) they explore the importance of prosociality to the retention of a toy 'cultural skill'. These experiments were designed to explore the relational difference that Henrich's 'genius vs. butterfly' thought experiment highlights: that prosocial relations are required not only for cultural transmission but for cumulative culture (viz. the high-fidelity retention of innovations that build on previous innovations, etc.). In the first section I followed Tomasello (1999) in identifying this as a core feature of human culture, and suggested that this is a particularly pertinent feature of scientific communities. In Muthukrishna and colleagues' experiments, participants were arranged into one of two groups and into one of ten cultural generations. In group A participants had access to only one cultural parent (a member of the previous generation). In group B participants had access to five cultural parents. Participants were rewarded in the task for both achieving the cultural product with a high degree of success *and* also for how well their immediate descendants in the next generation performed the task (in experiment one this was to use a piece of imaging software to create a target image; in experiment two the goal was to tie a knot for rock

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[6] The *types* of communication are also crucial – I return to this below.

climbing). Participants were only able to influence the behaviour of the following generation through mediated and controlled communication that they could construct to pass on instructions (in experiment one this was by a set of written instructions; in experiment two this was a short video)[7]. The upshot of both experiments was that by the tenth generation the performance of every member of group B (who had access to five models) was superior in their performance to members of group A.

Although intriguing, these experiments are limited by the fact that the task goal is not functional. As such, the assessment criteria in the experiment is merely about whether the cultural product was successfully copied without any consideration about whether this could be related to what role this cultural product achieves. This issue is mitigated in experiments by Derex and colleagues (2013) who used a computer simulation to test groups of participants at creating one of two cultural products – easy and difficult – that were used to attain in-game resources. Additionally, participants were informed that the cultural products could be modified so as to improve performance. As in the previous experiments, Derex and colleagues were also investigating the importance of social groups on the maintenance of cultural complexity across generations. They found that as group size increases not only is there a better retention of the cultural skill and product, but there were also more frequent improvements and diversity (2013 : 389).

In particular, it is this aspect of improvement and refinement across generations, and how this is fostered by prosociality, that I think is most relevant to science and technology studies. Henrich's gambit is that innovation in a community can occur in multiple ways (2016 : 213). So, whilst it is undeniable that some innovations are the products of intentional creative acts of genius; we should also recognise that they can also be the product of lucky errors, novel recombinations, and chance insights *that arise through the social interconnectedness of a community of enquiry across time*. Like Henrich, Tomasello emphasises how cooperative our species is in comparison to other primates (also see Dean et al 2012 for a nice set of comparative experimental results demonstrating this). He differentiates between two kinds of collaboration: [1] actual collaboration that takes place in the synchronic temporal plane; and [2] virtual collaboration which takes place across historical time (1999 : 41).

The capacity of humans to collaborate virtually across generations allows us to tackle problems that would otherwise defy us – e.g. cognitive tasks that involve regularities occurring at temporal scales that would otherwise be invisible (Boyd et al 2011; Henrich 2016; Shea 2009). Tasks such as farming are so variable that the probability of a single agent acquiring good practices and strategies through individual learning is vastly improbable in comparison to acquiring a relatively good practice from a cultural niche in which the knowledge and appropriate behaviour is imitated and inherited. As Shea puts it: "…the information available to individuals is just too impoverished to allow them on their own to build up much knowledge about likely crop yields" because cases like these involves outcomes

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[7] One could criticise this mediated aspect of the experiment because it separates and isolates the generations and so arguably abstracts out entirely the factor that the experiment is supposed to measure – prosociality. However, whilst I think it is important to recognise this limitation, it is also important to note that this is a lab-based experiment that sits within a wide range of ethnographic field work and theoretical modelling that suggests that prosociality is vital for human cultural evolution (see Muthukrishna et al 2014 : 1, 5-7 for details). Additionally, one can defend these experiments by arguing that a necessary aspect of lab-based experiments is that variables are appropriately controlled. And that this was a necessary first step in exploring sociality in an 'intergenerational' context in a lab-based setting. From this basis, future lab-based experiments could potentially explore exchanging the mediated communication for some other form of direct communication with a time constraint, etc.

that "…occur on a timescale that is of little use for individual learners" (2009 : 2435). Additionally, if it is a cumulative cultural niche, then knowledge and practices will become increasingly refined. The intergenerational transmission of partially accumulated knowledge allows for the detection of regularities at temporal scales which would otherwise be invisible to individuals within their limited lifespans. For instance, in the geographic information sciences, the task of mapping the entire surface of the Earth with a discreet framework (e.g. the Mercator projection) took more than four centuries and thousands of individuals – with a complete map not appearing until 1972 (Snyder 1987 : 41).

Henrich's major claim is that for a cultural species such as ourselves it is our sociality rather than innate intelligence that is more important for explaining our success (2016 : 228). He labels this provocative notion the "collective brain" (212). He goes on to argue that demographic factors – such as the size and interconnectedness of the group – are crucial for epistemic progress. Such claims have been previously explored in the philosophy of science literature. Thagard (1993) has likened scientific communities to communication systems and notes that they are replete with asymmetric communication channels (due to four factors: sparseness of connectivity; asynchronous communication; slow transmission; and incomplete transmission). This asymmetry can prevent groupthink by buffering the flow of information and can lead to cognitive diversity. Conversely, von Hippel (1994) has identified that "sticky information" – information that is hard to transmit – can lead to suboptimal explorations of epistemic landscapes. Furthermore, differing kinds of communication channels can impact on collaborative work and cognitive diversity: e.g. face-to-face between colleagues or in an apprentice-master relationship; journal articles and experimental reports; data sets; conference papers; textbooks – each of these has an impact on how information is transferred and processed. But although Henrich certainly overlooks these factors as well as questions concerning the composition of a community of inquiry (as is explored in theoretical models by Kitcher (1993), Weisberg (2010), and Zollman (2010)); I think that there is something additive here about the notion of virtual collaboration (as intergenerational innovation that is possible without intentional creativity). This can be clarified with a simple example.

According to anthropologists, the Inuit people of the artic region are regarded as one of the most adaptive cultures on the planet (Aporta & Higgs 2005). When the Inuit of west Greenland began adopting firearms they found that they were difficult to use whilst steering a Kayak (Boyd et al 2011: 10922). Thus, demonstrating the mutual interdependencies of tools and techniques in a particular community – what Hutchins has called a "cognitive ecology" (1995). In 1824 a prominent hunter tried to redesign and adjust his kayak so he could use a rifle. He made a rudder but it didn't work very well. Younger hunters tried to imitate him despite the lack of success partly because of his prestige. But they took to hiding the rudders under the waterline to hide their shame for not being able to do it very well. This unintentional and serendipitous innovation led to greatly improved performance.

Although deep understanding is often emphasised in scientific communities, here we have an example of how trial-and-error arising through social interactions in a sufficiently high degree can lead to progress. Arguably, there are many such cases in scientific practices. For instance, Nersessian's (2005) cognitive-historical analysis of a biomedical engineering laboratory (engaged in trying to create artificial blood vessels) discovered that many of the models and experimental apparatuses were gerrymandered and redesigned by successive members of the lab who built upon and adapted each other's designs across generations. As such, collectively they were able to gradually understand and tackle many sub-problems involved in trying to design artificial blood vessels (e.g. modelling the sheer forces involved). What is interesting in these adjustments is that although they are retained across generations of experimentalists – as PhD and postdocs join and leave the lab – they do not strictly have a shared or singular purpose. Instead, they are all working on subproblems that are not necessarily related. And yet, despite the nonlinear accumulation of refinements in the experimental equipment, epistemic progress can be made.

To return to the geographic information sciences, there are many examples of what D'Agostino evocatively refers to as soldiers (without generals) engaged in local, incremental "gradual attrition" of a particular problem space (2008 : 304). For instance, modern computers and the internet have made the production of thematic maps (the overlapping of geographic areas with data about people and places) far easier (Bray 2014 : 171-175). Since 1996 there have been a number of internet based geographic information systems (GIS) – the most famous of which is Google Maps (itself a product of numerous acquisitions of other companies and GIS, e.g. Where 2 Technologies, Earthviewer, etc.). A competitor, OpenStreetMap, demonstrates this even further. Inspired by the success of opensource networks such as Linux and Wikipedia; OpenStreetMap provides users with maps that are comprised entirely from data collected by amateurs – "crowdsourced cartography" – to avoid the monopolising of maps by governments and big companies (Bray 2014 : 186, 191). Each of these systems is the product of myriad interactions and refinements on shared frameworks and standards (e.g. the Mercator projection). Many of these improvements and refinements in these GIS come from non-intentional acts and the sheer quantity of individuals involved in their use and incidental advancement that arises out of these multiple connections.

4. Applications and speculations

The question now arises: how can these findings feasibly be used to structure scientific communities so as to optimise epistemic progress? There are a number of complicating factors in trying to generate these sorts of social interconnectedness that could be productive in modern scientific communities. Firstly, modern science is incredibly vast and diverse. As Braun and Schubert (2003 : 185) put it: the "explosion of knowledge" which began in the Enlightenment continues at an unprecedented degree into the current information engorged era, and this entails that "…it has become possible for an individual to comprehend only a few of the fragments". Such is the fragmentation of knowledge that some philosophers even debate the unity of science as a project (e.g. Dupré 1993; cf. Ladyman & Ross 2007).

Fahrbach (2011) notes that 80% of all scientific work has occurred since the 1950s, which indicates an exponential growth. As such, as time goes on and new fields and problem spaces continue to emerge it becomes increasingly difficult to imagine a pedagogical setting in which there is a sufficient degree of social interconnectedness between fields to facilitate productive virtual collaboration. This entails that the success of the many scientific fields into investigating nature creates a situation where:

> To avoid drowning in the ever expanding ocean of knowledge, each of us typically grasps for one or two floating spars which we clutch as if our life depended on them and thereafter seldom look to the right or left. To look beyond one's own spar is to be overwhelmed by the ocean's magnitude: better to remain ignorant of all but our own tiny province. (Braun & Schubert 2003 : 185)

As Andersen (2016) has observed, this abundance has led to an increase in both collaboration and specialisation. This relates to another complicating factor. Humphreys (2004) has written extensively on how much of modern science is heavily dependent on computers to tackle data-intensive problem spaces. For instance, DNA sequencing, turbulent flows in physics, and the search of exoplanets in astronomy are three examples of problem spaces that are infeasible to be computed "by hand". The reliance on computational resources combines with the radically collaborative nature of many modern scientific problems, where teams are composed of narrow specialists, to create an epistemic and social environment that is not conducive to the recombinatorial potential of virtual collaboration.

Whilst these circumstances are certainly problematic I suggest that they are not solely negative aspects. For instance, the intensely collaborative nature of many problem areas requiring increasing interdisciplinary cooperation – whilst certainly leading to increasing specialisation and narrowness of focus for some individuals – will also produce the conditions under which other agents have increased opportunities to engage in the sorts of ideational cross-pollination that engenders virtual collaboration. Indeed, D'Agostino identifies problem spaces which are "dynamically and complexly looped" as one's which are ripest for facilitating assembly bonus effects and promoting cognitive diversity because they defy resolution by solitary individuals (2008 : 304). However, the nature of problem spaces, or problem types also potentially raises a limitation on the potential for virtual collaboration. I.e. virtual collaboration – as epistemic progress through unintentional creativity – may only be possible with certain kinds of problems. Steiner's (1972) taxonomy of task types distinguishes between how the division of cognitive and physical labour can be divided in differing kinds of problems (he also demarcates some tasks which cannot be divided at all). For instance, he differentiates between problem types which are additive (where all members of a collaboration add their efforts together in some manner) and those which are disjunctive (where some procedure selects the efforts of only one member of the collaboration towards the task goal). Although Steiner's taxonomy was developed only in reference to actual collaboration, I think we can use it here without too much distortion to consider the limits of where virtual collaboration can occur. Viz. it is likely that some problem types may be more or less suited to virtual collaboration – but this is an empirical question.

Collaboration across specialisations also raises another problem related to the issue of sticky information discussed above. In the first section of this paper I noted that members of communities of enquiry are inculcated into sets of theoretical vocabulary and styles of thought. But in interdisciplinary work it can often be the case that members of differing epistemic communities lack a common tongue. In these situations, Galison (1998) notes that practitioners must create a "trading zone" in which "technical pidgins" can make the information of one specialist field accessible to members of other thought communities. Although this is an extra burden upon the epistemic agents involved, it is not an insurmountable one. Indeed, the development of shared technical vocabularies and the sharing of theoretical models and experimental designs between differing fields is a common practice (see Humphreys 2004).

As such, I suggest that interdisciplinary problem spaces and fields will be the areas ripest for virtual collaboration: the productive recombination of ideas across generations to generate novel insights that lead to epistemic progress that are not the product of intentional acts of creativity. This suggests a level of optimism with the current state of affairs in some scientific communities because, as Andersen (2016) notes, there is an increasing emphasis on interdisciplinary work. These interdisciplinary environments are ideal conditions for creating the multiple interconnections for differing ideas, theories, models, and experimental set ups that can then be recombined, reconsidered, and redeployed. With the growing number of active scientists in these areas, this increases the chances of lucky errors, intentional ingenuity, and chance insights.

One can perhaps contend that interdisciplinary research is already flourishing and producing viable new fields – e.g. biophysics (Braun & Schubert 2003) – and tackling interdisciplinary problems – e.g. the combined efforts of engineers and theoretical physicists to build high energy particle accelerators (Galison 1998). But I think that the notion of virtual collaboration adds a new element to these states of affairs. One which could, if properly exploited, lead to additional and supplementary epistemic progress. I suggest that this places an emphasis on increasing academic cross-training and examining areas lacking in trading zones. But also, to look for novel combinations between fields that are not normally recognised as complementary. The reasoning here is: that as the number and variety of interconnections increases so too does the possibility of a productive element emerging through sheer lucky error, chance, or combinatorial assortments without intentional creativity (see Henrich 2016 : 213)[8]. Currently, this is arguably an underexploited aspect of the sociality of scientific communities – with some fields deemed anathema or totally unrelated to one another. Although speculative, tapping into the abundance of interdisciplinary work as a resource for epistemic progress offers an opportunity for novel contributions which, because of the intergenerational structure of virtual collaboration, could lead to tackling problems that defy synchronic and straightforward cognitive assaults.

5. Conclusion

There is much research in science and technology studies and philosophy of science into the structure of scientific communities across both the synchronic and diachronic temporal planes. However, an underappreciated aspect of the intergenerational structure of scientific communities is the potential for virtual collaboration: the re-combination of culturally accumulated knowledge across generations into novel forms without intentional ingenuity. Virtual collaboration is a distinctive feature of the human species that allows us to tackle problems that would be beyond a single generation. Given the increasing complexity of scientific problem spaces and the requirement for interdisciplinary teamwork, there is an opportunity for this form of epistemic engineering by *invention through bricolage* to be utilised. Alongside other attempts to reorganise the structure of scientific communities, the species-specific factor of virtual collaboration suggests that science pedagogy and apprenticeship should involve interdisciplinary components to facilitate the production of trading zones and seed potential novel re-combinations of the vast amounts of previously acquired knowledge about nature.

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[8] It should be noted that each community of enquiry will have its own history of accumulated knowledge – including instances of virtual collaboration. Here I have made no distinction between cases which occur within a particular tradition and instances that occur in interdisciplinary work. Indeed, I have argued that virtual collaboration is more likely in the latter. But, whether these two forms are different in kind or similar is something I leave to be explored in future work. [I thank an anonymous reviewer for helping me to clarify this point].

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