1. Education for science and democracy

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Debates concerning school curricula for science often focus on questions of what kinds of knowledge should be represented. For example, curriculum scholars have debated whether school science should continue primarily to be as focussed on such theoretical knowledge as classical mechanics and evolution as it has in the past. Some (e.g., O'Reilly and McNamara, 2007) have presented evidence that such explicit knowledge predicts curriculum progress. Others advocate for a shift in curriculum towards scientific thinking (e.g., Gasparatou, 2017), or towards scientific literacy and applications of science to 'real world' situations (e.g., Crowell and Schunn, 2016). Yet others (e.g., Gallagher, 2000) argue that theoretical knowledge is a prerequisite for all of those things. There is another literature, albeit less extensive, on the kinds of *dispositions* that science educators should seek to inculcate. Much of this research addresses the effects of inquiry learning on dispositions towards critical thinking (e.g., Arsal, 2017) and motivation for learning (e.g., Cairns and Areepattamannil, 2019).

In the background of debates about knowledge lie questions about the kinds of *cognition* that students must engage in to learn it – remembering information, developing conceptual schemata, reasoning from evidence, solving problems, and so on. But while cognitive development is necessary for learning to think like a scientist, it is not sufficient. The ways in which knowledge is deployed must also take *dispositions* into account. Scientists must weigh the merits of theoretical claims on the basis of evidence and reason. To do this, they must set aside ubiquitous human tendencies such as confirmation bias (e.g., Kappes et al., 2020) and motivated reasoning (e.g., Kraft, Lodge, and Taber, 2015). Scientists must embrace being wrong and see disagreement as a source of theoretical refinement, rather than as a threat to their cherished ideas.

Another curriculum area in which similar issues pertain is citizenship education. Like science education, citizenship education has traditionally focussed on propositional knowledge. Students might learn about the functioning of parliaments and electoral systems, or the separation of powers. However, there is evidence that this approach does little to improve citizens' functional long-run civics knowledge (Shapiro and Brown, 2018).

Beyond questions of explicit knowledge, citizenship, like science, has a dispositional aspect in respect of the importance to democracy of an environment that promotes contesting ideas. Free and fair elections are a means of implementing modern liberal democracy, but they do not provide its fundamental underpinning. For reasons we will return to, we argue that the cultural lynchpin of democracy is open debate.

Science and citizenship education, then, have in common a need to inculcate respect for, and a willingness to participate in, a contest of ideas. In this chapter, we first discuss the philosophical relationship between science and democracy with reference to the literature on 'deliberative democracy', to Karl Popper's conception of science, and to more recent theories of collective knowledge. We then identify some of the ways in which the contest of ideas in both realms is put at risk by contemporary social forces. Finally, we suggest an educational approach to counteracting those forces inspired by deliberative citizenship education, to help safeguard both science and democracy.

SCIENCE AND DEMOCRACY

The leading account of democracy in the academy today is the theory of deliberative democracy (Bohman and Rehg, 1997; Elster, 1998). For these theorists, a central feature of democracy is deliberation, a kind of discourse that elevates reason-giving argumentation over force, fiat, or the mere expression of preferences; in a truly deliberative society, arguments are settled not by coercion but by 'the forceless force of the better argument' (Habermas, 1981, 1.47). For some deliberative democrats, deliberation is more than something that might simply emerge from a commitment to democratic ideals; rather, the processes of democracy itself are justified mainly because they allow us to run our affairs in a manner than qualifies as deliberation (e.g., Cohen, 1996).

With its emphasis on reason, empiricism, and argument, the deliberative democratic vision already draws democracy quite near to science. Nevertheless, the generality of the deliberative ideal means that democracy remains, in this vision, more akin to rationalism in general than to science in particular. In what follows, we will make use of some of the ideas of Karl Popper to argue that democracy and science in particular can be viewed as natural analogues. We close the section by going beyond Popper's ideas to argue that democracy can even be viewed as a distributed computational system involved in large-scale information-gathering – a kind of mass science, as it were.

One of the most influential treatises on the philosophy of science of the twentieth century was Popper's 1934 *Logik der Forschung*, first published in English in 1959 under the title *The Logic of Scientific Discovery* (Popper, 1934/1959). Popper also authored of one of the most influential works of political philosophy of the twentieth century. His 1945 book *The Open Society and Its Enemies* was written during his time at what was then Canterbury College in the University of New Zealand after he had come to the country as a refugee from the Third Reich during World War II. As an Austrian Jew fleeing the Holocaust, Popper had good reason to analyse threats to open society and democracy.

To achieve pre-eminence in two such apparently disparate domains is an impressive scholarly feat. However, while there is no doubting Popper's genius, the two works have more in common than a naïve reader might expect. A confluence of Popper's scientific and political thought is evident even in his early writings. Lefevre (1974) notes Popper's view that 'some of the traditional defences of open democratic systems … were coupled with epistemologies which, by misunderstanding the problematical character of science, had unwittingly laid the foundation for authoritarian theories of government' (p. 95). At the same time, Popper observed that 'only in an open society, in a society which tolerates and respects many views and many opinions, can we hope to learn from our mistakes and so get nearer to the truth'; and hence 'it is only in an open society that science is unfettered' (Popper, 1963/2008, p. 237). Popper clearly thought that there was a complementarity, even a similarity, between science and democracy, despite the fact that he never produced a fully developed theory of this connection (but see also Popper, 1988/2016 for some further thoughts on the topic).

In what follows, we note and develop a few of what we take to be the main analogies between democracy and science. Even though not all of these views can be found stated explicitly in Popper's published writings, we see this theory as sometimes implicit in what Popper did write, and always in the broader spirit of Popper's thinking on science and democracy. In our view, there are at least three important aspects of Popper's scientific epistemology that resonate with features of open democracies.

Provisionality and Fallibilism

A logical consequence of Popper's articulation of *fallibilism* in science is that ideas and theories are always *provisional*. Formally, fallibilism represents a break with the positivism of the nineteenth century, under which the goal of science was to use inductive processes to work towards objectively true theories. Fallibilism, recognising fatal flaws in the inductive approach, puts an emphasis on the reduction of error rather than on the identification of truth. Under a fallibilist approach, the job of a scientist who proposes a theory is to set about *disproving* it. To the extent that repeated attempts to falsify a theory fail, that theory gains validity. No theory, however, can ever be recognised as having the final word. It is expected that theories will be refined and sometimes completely overturned by new evidence.

Even if a theory *were* true, there is no logical method by which it could be proven so. Popper's 'black swan' thought experiment demonstrates the limitations of induction: A theory that all swans are white can never be proven, because it is always possible that non-white swans exist without (yet) having been observed. On the other hand, as Popper put it, while 'no number of sightings of white swans will ever prove the theory that all swans are white … the sighting of just one black swan may disprove it' (Popper, 1934/1959, p. 27). Under the fallibilist approach then, theories are never proven, but they do gain in validity if repeated attempts to falsify them fail.

Just as theories are provisional in science, policy is provisional in democracy. Public policy can be viewed as analogous to scientific theory in the sense that it must be subject to revision when it is believed to be in error. In the case of science, revision occurs in response to new evidence, or new interpretations of existing evidence. In the case of democracy, it occurs in response to the results of a policy, changes in the socio-economic environment, and shifting values.

We will return to fallibilism in the context of educational approaches to preparing young people to think like scientists and democratic citizens. We will argue for cultivating fallibilism, not as a philosophical doctrine, but as part of a deliberative disposition. That means inculcating an attitude that even one's deeply held views can be improved, and that we can learn from those with whom we disagree if we are prepared to discuss differences openly.

Contestability

In science, the principle that theories are contestable is a corollary of them being provisional and of the requirement that they be falsifiable. Formally, every time a scientific investigation is carried out, it is testing a theory with evidence. Because of the fallibilist principle, a study can disconfirm, but never categorically confirm, a theory. The interpretation of evidence in science is similarly subject to contestation. Scientists may dispute the logic of an existing theoretical interpretation or propose alternative explanations that better account for the observed data.

In a political context, contestability is a vital principle in any open society. In a functional democracy, public debate is open and continuous. It is supported by a free and critical media that holds governments to account and seeks to represent viewpoints that contest their policy positions. It is further supported by an informed voter base, who are able to contest policy ideas with one another, in good faith, without fear of censorship or censure. Contestability cannot be protected, either in science or democracy, by rules or laws. If it is not held as a value by scientists and citizens respectively, it will not survive. Both science and democracy would thereby lose a great deal of their power to refine ideas.

Incrementalism

When the predictions of a scientific theory are falsified by an experiment or other set of observations, that theory is more likely to be refined than to be abandoned altogether. A theory that has been extant for any length of time, and has already survived attempts to falsify it, has, by definition, accumulated substantial validity. The falsification of specific predictions in a single study, then, does not usually refute it in general (Popper's 'black swan' notwithstanding). An incremental modification that accommodates the new evidence is usually more epistemically efficient than wholesale abandonment.

An exception to incremental change in science is the occasional *paradigm shift* (Kuhn, 1962). Kuhn recognised that the usual mode of scientific theorisation, which he referred to as *normal science*, does indeed operate incrementally. However, normal science is punctuated by periods of *revolutionary science*, during which radically new theorisation occurs. Paradigm shifts are precipitated by an accumulation of incremental modifications and unsolved anomalies, not just in theories, but in whole *systems* of theories (i.e., in paradigms). At a certain point, an existing paradigm becomes unwieldy and untenable as result of this accumulation. What ensues is not just a new theoretical framework but, very often, an entirely new way of looking at the world. One of Kuhn's more controversial claims was that, because they reflect different worldviews, paradigms are *incommensurable*; he claimed that there is no way to adjudicate their relative validity. It is well beyond the scope of the present discussion to analyse this claim. For our purposes it is enough to note that paradigm shifts are rare, and that incremental change is the usual scientific *modus operandi*.

The term *incrementalism* was coined by Lindblom (1958), rather than by Popper himself, and in relation to organisation theory rather than science or politics. Nonetheless it is consonant with Popper's (1945) concept of 'piecemeal social engineering'. Popper noted that authoritarian political decision-making fails, among other reasons, due to poverty of information. The effects of large-scale, top-down programmes of change are unpredictable, both because of the complexity of social systems and because constantly changing conditions call for agile responses.

In liberal democratic societies, piecemeal social engineering involves incremental change in response to the aggregate requirements of a populace. Those in power are incentivised by the regular occurrence of elections to monitor public opinion and to aim to satisfy it. The outcome of an election acts as a gauge of their success. If their policy decisions have improved social and economic conditions, a government is more likely to be re-elected than it is if conditions have deteriorated. A series of small changes guided by feedback from the populace is the approach most likely to yield improvement. Poverty of information makes large-scale change much riskier.

DEMOCRACY AS AN EPISTEMIC SYSTEM

As we saw above, Popper viewed the open society as crucial in enabling genuinely rational and scientific – that is, genuinely *critical* – thought to take place. Even in *The Open Society and Its Enemies*, Popper prepared the ground for a fuller account of how certain social institutions might make up a system for gathering and diffusing knowledge. 'It may be said', he wrote there, 'that what we call "scientific objectivity" is not a product of the individual scientist's impartiality, but a product of the social or public character of scientific method; and the individual scientist's impartiality is, so far as it exists, not the source but rather the result of this socially or institutionally organized objectivity of science' (Popper, 1945, p. 426). Indeed, Ian Jarvie has argued that there is a social element to Popper's thinking about science that can be found as far back as his early masterpiece on scientific method, *The Logic of Scientific Discovery* (Jarvie, 2022).

However that may be, Popper never formulated a full theory of how political and social institutions might best encourage the progress of science and of rational inquiry. Luckily, in more recent decades several thinkers have converged on the idea of society – and specifically, of republican or democratic society – as a kind of knowledge-production (or knowledge-discovery) system. Jonathan Rauch, in his recent book *The Constitution of Knowledge*, has argued that scientific, political, and other institutions can, if suitably arranged within an over-arching republican order, constitute an epistemic system that both gathers knowledge and has some capacity to self-correct (Rauch, 2021). Rauch's republican view is only one step away from the idea of democracy – particularly deliberative democracy – as a system for gathering and processing information. In this view, which owes something to Hayek's understanding of the nature of 'dispersed knowledge' (Hayek, 1945), deliberative democracy has an 'epistemic' aspect. It is, in other words, encouraging of high-level discussions among citizens, partly as a means of improving our *knowledge* of the world and hence our decision-making (see esp. Cohen, 1989; Ober, 2008).

We find much that is appealing in this latter idea, of democracy as a kind of aggregator and processer of mass preferences and views. A society in which open debate occurs at all levels – from interpersonal conversations to the representation of differing viewpoints in the media to parliamentary debate – can be understood as a distributed computational system (see Rumelhart, McClelland, and PDP Research Group, 1987). There are many formal instantiations of such systems, which are sometimes not entirely accurately, known as 'neural networks'. A unifying attribute, however, is that they comprise many individual nodes, each holding a very small amount of information. The nodes are highly interconnected, with activation flowing from one to another, ultimately settling on a pattern of activation in an 'output layer', which provides the result of the computation. By tuning the weighting of the connections between nodes, based on feedback, the system can 'learn' to successfully perform classification tasks.

Without wishing to stretch the analogy too far, conceptualising a democratic society as a distributed computational system yields some valuable insights regarding the value of a free flow of information. Individuals comprise the nodes and innumerable verbal interactions represent the flow of information through the network. Although, taken individually, these interactions are highly error prone, in aggregate they work towards improved policy positions. Viewed in this way, elections are decision-making mechanisms that reflect the state of the system (the aggregated views of a society) at a point in time. Without a culture in which open debate is possible, however, the 'device' functions sub-optimally. A critical aspect of that culture is widespread understanding that public policy is provisional and 'falsifiable', albeit in a less formal sense than that expressed by Popper in relation to scientific theories.

Conceptualising a scientific or political community as a distributed computational system also provides a further reason that incrementalism (which we mentioned above) tends to work better than revolutionary change. As we have noted, such systems improve their functioning by tuning the weightings of connections between nodes within the system. Feedback from the environment, which is continuous and ongoing, provides the information necessary to guide this tuning process. Because the nodes are massively interconnected and interactive, large changes in weights in a short time render the system computationally unstable. Incremental change allows the system to keep pace with environmental change without incurring undue instability. The process by which a society tunes itself to changing conditions is greatly supported by the contest of ideas and by widespread understanding of its importance. In the following section we explore some contemporary threats to the contest of ideas in western democracies.

RISKS TO SCIENTIFIC THINKING AND DEMOCRATIC VALUES

In both science and democracy, unthinking obedience to authority and undue social conformity are obstacles to sound theoretical development in science and sound public policy development alike. Both reduce the likelihood that ideas will be rigorously contested. Both are perpetual enemies of science and democracy; perpetual, because they appear to be natural human proclivities (see for example, seminal work by Milgram (1963) on obedience to authority and by Asch (1951) on social conformity). If that is so, then the value base conducive to scientific thinking and open society must constantly be maintained to hold entropy at bay.

In addition to these perennial enemies, science and democracy face new threats in the forms of political polarisation and psychological fragility. As we review below, there is evidence, especially from the United States, showing increasing dislike and distrust between citizens of different political persuasions. The deleterious effects of such polarisation on the democratic contest of ideas are obvious. Science also gets more difficult to conduct in a polarised environment. That is because scientific questions are more likely to become politicised, and theoretical positions to become associated with political decisions.

Across the world, rates of anxiety and depression have sharply increased over the last decade, especially in young people (e.g., World Health Organization, 2017). Again, a psychologically fragile population is not one that is well equipped to participate in contests of ideas, whether in the domain of science or of politics. By their nature, contests of ideas can be psychologically bruising. Having one's cherished ideas challenged can be painful. Inevitably, we encounter ideas that occur as unpleasant or even offensive. If people have not developed dispositions that give them psychological resilience, these factors are likely to lead to withdrawal at best, and active attempts to censor others at worst. In the following sections we consider in more detail authoritarianism, social conformity, polarisation, and psychological fragility as threats to open society and to science.

Authoritarianism

Authoritarianism, by definition, involves policy being determined hierarchically, with no contest of ideas necessarily taking place at all. In the most authoritarian situation, a despot makes all decisions without challenge. In less extreme cases, a small decision-making cadre may contest ideas amongst themselves. In either case, however, a vast amount of information and computational power distributed through the system (society) is wasted. Typically, authoritarian policy makers engage in censorship and, frequently, in persecution, to inhibit dissent. Even if they do not, the lack of a mechanism – typically an election – to test the effects of policy decisions, means that those decisions are insulated from the benefit of any contest of ideas that takes place within the population. In science, the provision of funding for scientific programmes is one way in which authoritarian control over scientific discourse may be maintained. At a more local level, professors who control research resources and publication processes may inhibit younger, less established researchers from challenging their theoretical positions. This may occur through controlling resources or withholding opportunities for advancement.

Social Conformity

Like authoritarianism, social conformity results in a wastage of information and computational power, although it inhibits the flow of information into sound policy making in a different way. A conformist society, almost by definition, is one in which people are uncomfortable with disagreement. Most people adopt positions that they believe to be consonant with dominant perspectives, at least publicly. If they do take a dissenting position, they will typically be muted about expressing it. Inhibiting the contest of ideas in this way reduces the quantity and quality of interaction between nodes in the system (citizens in the society). In this situation, even if government does not operate in an authoritarian manner, the information available to inform policy will be biased (in the direction of socially acceptable viewpoints) and the feedback mechanism (elections) will be noisy.

While scientists may be more resilient to the forces of social conformity than average because of their scientific training, as human beings they remain subject to them. They may tailor their research programmes to avoid areas that seem too controversial. They may avoid emphasising aspects of their data that support socially unpalatable conclusions.

Science is never ‘settled’. Claims in support of certain policy positions – for example in relation to climate change or COVID vaccines – on the basis of scientific consensus *alone* are invalid from a scientific perspective. Consensus, while it might be based on evidence and sound argument, is neither of these in itself. It is necessary to take certain policy decisions informed by the preponderance of scientific evidence available at the time. Policy decisions cannot wait for scientific certainty, which, as we have already discussed, will never arrive. But while consensus (or near consensus) amongst scientists on a theoretical stance may be an adequate justification for a policy, it does not suffice as a *scientific* argument. The history of science is replete with examples of minority positions eventually becoming ascendant on the basis of valid scientific inquiry and argumentation. Those who take dissenting positions, then, must be enabled to argue for those positions using evidence and reason.

Polarisation

Surveys of American citizens conducted by the Pew Research Center (e.g., Pew Research Center, 2022) show an alarming growth in the mutually negative perceptions that Republican and Democratic voters have of one another. The 2022 report shows precipitous increases between 2016 and 2022 of the proportion of each party's supporters who rate supporters of the other party as more closed-minded, dishonest, immoral, unintelligent, and lazy than other Americans. Similar dynamics, albeit less extreme, can be observed around the world (McCoy, Rahman, and Somer, 2018). Political philosophers Aikin and Talisse (2020) summarise the situation thus: 'contemporary democracies are failing to handle political disagreement properly … Citizens … are growing increasingly inclined to regard those with whom they disagree over politics to be not merely incorrect, but depraved, dangerous, and threatening to democracy itself' (p. 10).

Rising polarisation cannot be good for the democratic contest of ideas. If people with opposing politics each believe their opponents to be unintelligent, they are unlikely to take their arguments seriously. If they rate opponents as immoral, they are likely to think their arguments are ill-motivated. People may even conclude that their opponents are unfit to participate in democracy and attempt to exclude them from it. Polarisation thus threatens the very foundation of democracy: the belief that all citizens should have an equal say in shaping the social order (Aikin and Talisse, 2020).

There is another, more technical, reason that polarisation is bad for the contest of ideas. We have conceptualised elections as a method of testing the state of the system – the body politic – at points in time, to check that incremental policy change is progressing in the direction of people's preferences. That mechanism is most sensitive when a preponderance of voters is located near the middle of a viewpoint distribution. Under these circumstances, an incremental change of a given magnitude will shift the perceptions of more voters – whether positively or negatively – than it will when the middle is 'hollowed out'. Thus, larger, more destabilising policy shifts are more likely in a polarised environment in the context of politicians' quests to capture votes. Polarisation, then, threatens Popper's 'piecemeal social engineering'.

Under the distributed computational model of democracy that we have laid out, a polarised society means that the network of nodes comprising the system has effectively split into two parts, with only sparse connections between them. When this happens, a feedback loop is likely to be established, resulting in the two sub-systems moving further and further apart. That is because the state of each sub-system is largely determined by its own internal interactions, with little input from the other. Furthermore, the mutual animosity between them drives each to react against the ideas of the other.

In a harmonious body politic, views on given policy questions are more likely to be held on their perceived merits than in a polarised society. In the latter, they are more likely to be held for 'tribal' reasons – as markers of affiliation, rather than argued for on the basis of reasoning. In these circumstances, the basis of people's viewpoints moves away from reason, towards loyalty. This factor exacerbates the difficulty of piecemeal social engineering; tribal loyalists dislike or distrust anything that looks like a concession to the other side. Furthermore, tribalisation also causes the multivariate distribution of viewpoints on a range of issues to become more internally correlated within each sub-system. In other words, because particular constellations of beliefs become markers of loyalty, a person's viewpoint on one issue is more likely to predict his or her viewpoint on another.

Finally, political polarisation undermines some of the dispositions that scientists must cultivate to contest ideas with humility, especially fallibilism and provisionality. Both are counter-intuitive and run up against cognitive biases such as motivated reasoning and confirmation bias, as well as the temptation to personalised (*ad hominem*) arguments. As human beings, scientists are predisposed to these human foibles, even if their training gives them some equipment to hold them at bay. In a politically polarised society, scientists may also become tribal in their beliefs, disposing them to evidence that supports those beliefs, while ignoring or downplaying counterevidence.

Psychological Fragility

Lukianoff and Haidt (2018) cite data showing a sharp increase in the numbers of people, especially young people, exhibiting anxiety and depression since the middle of the 2010s. They suspect two culprits – risk-averse parenting and the dynamics of social media. In the latter regard, they note that the sharp increase in depression in young women, in particular, coincided with Facebook becoming available to adolescents. Whatever the reason, research data are clear that young people report anxiety and depression much more than they used to (see for example, Keyes et al., 2019). Lukianoff and Haidt connect the apparent increase in these mental afflictions with rising censoriousness, especially on university campuses. They argue that mental fragility can lead to an attitude that ideas can, of themselves, be harmful. Increasingly, there is tendency to eliminate the expression of such ideas, rather than to meet them with evidence and reason.

Science and democracy are both founded on the meta-values of liberalism. By ‘meta-values’, we mean that liberalism encompasses a set of principles that allow the maximum flourishing of diversity in values. As Fukuyama (2022) put it, ‘classical liberalism is a big tent that encompasses a range of political views that nonetheless agree on the foundational importance of equal individual rights, law, and freedom’. The maximum size of the ‘tent’ is defined by Popper’s (1945) ‘paradox of tolerance’. Popper pointed out that liberalism and, by extension, the great range of value systems it enables, could be brought down if illiberal or anti-liberal actors – in particular, those who seek to replace arguments with coercion – are ceded too much ground (Kierstead and Boyd, 2022).

Psychological robustness is essential to the maintenance of liberal values. The contest of ideas, which we have argued here is the cornerstone of liberal democracy may, at times, offend. If avoidance of offense is widely seen as a reason not to engage in the contest of ideas, or to prevent those whose ideas are deemed offensive from doing so, we approach a paradox of tolerance. If science and democracy are to function optimally, there can be no sacred ideas in either domain.

Lukianoff and Haidt invoked Taleb’s (2013) concept of ‘antifragility’ as a way to counteract the effects of anxiety on the willingness of young people to engage in contesting ideas. Briefly, Taleb noted that, whereas most objects are either fragile and break easily, or are resilient and resist being broken, some systems are *antifragile*. That means they get stronger under optimal levels of stress. Examples include the human immune system, bones and, Lukianoff and Haidt argued, human psychology. If people are exposed to ideas they find difficult on a voluntary basis, they become more able to process them, to consider their merits, and to allow them to influence their own thinking.

In the final section, we turn to the question of how antifragility may be harnessed in support of educating young people for science and democracy.

CULTIVATING DISPOSITIONS FOR SCIENCE AND DEMOCRACY

As noted at the outset of this chapter, historically, science education has tended to focus on theoretical knowledge. Given that scientific theories provide the best available understanding of phenomena in the natural world, this approach has much to recommend it. Such understandings convey numerous benefits in life and work. One of these is the ability to participate meaningfully in public debates in which scientific questions have bearing on questions of social or economic import.

School science also often includes science investigation – practical experience of the methods by which theories are tested. Typically, though, the logic of these methods is not emphasised as much as the procedures are. There are sound pedagogical reasons for this, but nonetheless, it entails a lost opportunity. As argued by McIntosh and Johnston (this volume), science epistemology connects the theoretical and investigative aspects of science; it lays out the logic by which the investigative methods of science test its theoretical claims. It also lays out the logical process of reasoning about the evidence revealed by investigations.

A greater emphasis on epistemology would make it clearer to students what science is and help to enable them to think like scientists. Epistemology is at the heart of science. Its processes are an antidote to sacred belief: neither the fact that something is held sacred, nor that it is a traditional belief, is a valid argument in favour of a theory from a scientific perspective. If science education is to be a vehicle to teach young people how to contest ideas, rigorously and in good faith, greater emphasis on the epistemology of science would be beneficial. The epistemology of science encompasses the nature of the discipline as a way of structuring knowledge and, critically, the logic of its powerful methods for testing theoretical claims. Without at least some understanding of the latter, theoretical knowledge is merely received wisdom. Another important aspect of science epistemology is the understanding of what constitutes valid argumentation in the discipline.

The pedagogical task of using investigation to instil understanding of science epistemology is formidable. There are at least three major elements involved. The first is understanding the theoretical claim to be tested. The second is the investigative procedure itself. The third is the epistemic knowledge that bridges the two – the logic by which the investigative procedure tests the claim in question, and the processes of argumentation by which competing claims are adjudicated using evidence.

From a cognitive perspective, the pedagogical challenge here is primarily one of managing cognitive load. The term *cognitive load* refers to the extent to which a task occupies the resources of working memory (e.g., Baddeley, 2010; Sweller, this volume; Ashman, this volume). Working memory is a short-term memory system, the contents of which are held in conscious awareness. Its contents can therefore be thought of as the contents of consciousness at any given moment. Those contents are amenable to manipulation and reason – so working memory is the store of the information that we are 'thinking about'.

Working memory can take input either from the sensory environment or long-term memory. As the system that supports our ability to reason about information, it is very powerful. However, it has a very limited capacity and decays within a few seconds unless the information there is rehearsed. When it is overloaded, as often happens when learning new and complex things, confusion results. Students who lack confidence, or who struggle frequently with cognitive overload, are likely to become frustrated and eventually demotivated. There is a risk, then, that poor pedagogical management of cognitive load will impact negatively on students' learning efficacy.

The best way to manage students' cognitive load is to ensure that material is presented at a pace that allows them to digest it without too many experiences of cognitive overload. Material that is foundational to advancement must be learned to the point of cognitive automaticity, at which point it no longer consumes cognitive resources. Even so, there are instances in which a degree of cognitive overload is almost inevitable. McIntosh and Johnston (this volume) argue that using science investigation to inculcate knowledge of science epistemology is one of these situations. Arguably, at school level, this task is just too demanding. If so, the tendency to treat investigation in school science programmes as little more than a set of procedures to carry out might be justified.

Fostering a Deliberative Disposition

An alternative to explicitly teaching epistemology, whether it is connected to investigation or not, is to inculcate a deliberative disposition. A deliberative disposition is what enables citizens to partake in the mutual exchange of reasons necessary to democratically resolve contentious political issues – it is quite simply 'the willingness and ability to deliberate' (Gutmann and Thompson, 1998, p. 52). In the context of citizenship education, students acquire a deliberative disposition when they internalise the key values of autonomy and mutual respect, and the habits that fulfil these values, such as listening to other perspectives, evaluating the reasons supporting their own and others' opinions, and changing their mind if warranted (Hanson and Howe, 2011). Further, students should be able to evaluate deliberative processes themselves, both in the classroom and in society, to ensure that they continue to enable autonomy and mutual respect for all (Nishiyama, 2021).

Bridging this work with Popper's, we propose that a genuinely deliberative disposition should be informed by fallibilism. Fallibilism is arguably the most central concept in science epistemology because other elements we have discussed here – provisionality and contestability – emanate from it directly. If a deliberative disposition informed by fallibilism were in place by the time students start to approach science as a discipline, the link between investigation and theory would be much easier to grasp. It would mitigate the cognitive load associated with using investigation to connect theoretical science with its epistemology. There are both cognitive and affective reasons for this.

Cognitively, applying a deliberative principle is demanding. Automatising the propensity to question ideas and find flaws in arguments – especially one's own – and to listen attentively to arguments made by others can reduce the load associated with reasoning. With practice, the process simply becomes less demanding. From the affective perspective, challenging beliefs and ideas can be confronting and even provoke anxiety (see Lukianoff and Haidt, 2018 for a discussion). As a result, it can cause an autonomic response (Sharma et al., 2011) that interferes with the executive functioning required to engage rigorously in a reasoning process (see Forte, Favieri, and Casagrande, 2019, for a review). Research on Cognitive Behavioural Therapy (CBT) has reiterated the well-known principle that gradual, voluntary exposure to situations that cause anxiety will reduce that anxiety over time (Heinig et al., 2017).

Elements of a deliberative disposition informed by fallibilism include intellectual humility and a propensity to seek disconfirmation of our ideas rather than to confirm them. If we are not prepared to interrogate our ideas to find out what's wrong with them, we have little prospect of improving them. As we argued earlier in the chapter, a deliberative disposition is necessary in both science and democracy. Including training in such a disposition, therefore, is important for all students, not just those few who will go on to study science at university.

In the final section, we explore a pedagogical approach to establishing a deliberative disposition in science education. In addition to making students more willing and able to engage in debate, such a disposition may reduce the cognitive load associated with learning science epistemology and keep affective responses that inhibit executive function in abeyance.

ARGUMENTATION AND REASONING AS A PREPARATION FOR CONTESTING IDEAS

How might we inculcate a deliberative disposition (and even, perhaps, a deliberative disposition grounded in fallibilism)? A recent theory, the argumentative theory of reasoning developed by Mercier and Sperber (2018), predicts that training in logic will not be enough. Mercier and Sperber hypothesise that the human capacity for reason evolved in a social context – that is, so that human beings could solve problems collectively rather than individually. The fact that using reason can increase our individual knowledge is, according to the theory, an epiphenomenon. The adaptive drive for the capacity for reason is instead postulated to have been collective; we reason in order to exchange views.

Evidence in favour of the theory comes from studies showing that, when people are involved in collective reasoning exercises, they produce more accurate (Klein and Epley, 2015; Trouche, Sander, and Mercier, 2014) or more sophisticated (Woolley, Aggarwal, and Malone, 2015) solutions than they do when they reason individually. Mercier and Sperber argue that one of the reasons for this is that reasoning works better when we are evaluating arguments than it does when we are constructing them.

When we're constructing an argument and reasoning about it individually, we are susceptible to confirmation bias (Knobloch-Westerwick, Mothes, and Polavin, 2020). Confirmation bias is the ubiquitous human tendency to place more weight on ideas we already hold than on evidence that might refute them. We are also lazy – we don't tend to consider all of the best counterarguments to our position (Klayman, 1995). When we are engaged in reasoning with others, we tend to be held to a higher standard of argument. People will find flaws and counterarguments to other people's views much more readily than they will to their own because they are, by definition, less susceptible to confirmation bias.

Empirical research conducted with children supports the predictions of the argumentative theory of reasoning. Like adults, children reason better in argumentative contexts than by themselves (Mercier, 2011). Children as young as two engage in argumentation, both to evaluate arguments (Corriveau and Kurkul, 2014; Mercier, Bernard, and Clément, 2014) and to produce them (Köymen, Rosenbaum, and Tomasello, 2014; Köymen, Mammen, and Tomasello, 2016); and argumentation skills improve with development (Arcidiacono and Bova, 2015; Köymen et al., 2020). By the age of eight, many children are able to distinguish between good arguments and bad ones, to modulate their argumentation strategies to their audience, and to produce sophisticated counterarguments (Domberg, Köymen, and Tomasello, 2018; Köymen et al., 2020; Soley and Köseler, 2021).

The argumentative theory of reasoning holds powerful implications for science education (Mercier, 2016). Chief among them is the idea that engaging young people in classroom argumentation can improve their scientific understandings and their ability to examine conflicting viewpoints. Considerable empirical research supports this proposition. Students who exchange arguments deepen their understanding of scientific concepts (Bathgate et al., 2015), appeal to evidence more and connect evidence and conclusions more clearly (Mayweg-Paus and Macagno, 2016), and develop a more sophisticated epistemological stance (Lordanou, 2016). There is also evidence that classroom argumentation can reduce polarisation (Clark, 2021; McAvoy and McAvoy, 2021). For example, using a large and diverse sample, Clark (2021) found that people who recalled discussing political issues and expressing different opinions at school showed less affective polarisation as adults.

Even if human beings have evolved a predisposition for argumentation, young people are far from perfect arguers. They can struggle to support their views with evidence (Miralda-Banda, Garcia-Mila, and Felton, 2021), often shy away from engaging with others' views (Polo, 2020), and sometimes take offense when others disagree with them (Garrett, 2020). Consequently, students need help from teachers to improve their argumentation skills. Emphasising the value of different perspectives (Thiebach, Mayweg-Paus, and Jucks, 2016) or prompting students to think about the concept of evidence (Miralda-Banda et al., 2021) have been shown to be effective strategies to help students argue more persuasively. Further, establishing a cooperative, rather than competitive, atmosphere, may be more conducive to good argumentation. Young people tend to produce more sophisticated and less biased arguments when they argue in order to reach consensus rather than to win (Domberg, Köymen, and Tomasello, 2018; Garcia-Mila et al., 2013). Cooperation may also be more effective than competition to reduce polarisation: In McAvoy and McAvoy's study (2021), high school students participated more, felt more comfortable, and reached more consensus when discussing controversial issues in a cooperative setting rather than in a competitive one.

Controversial socio-scientific issues like climate change or COVID vaccines (not to mention political issues like systemic racism or religious freedom) may evoke strong emotional reactions that can disrupt cooperative argumentation. In 'hyperpolarised' contexts such as the United States, there is also a very real risk of students becoming violent when they discuss such topics. For example, Garrett and Alvey (2020) describe a tumultuous discussion on same-sex marriage in a US secondary classroom in which some students made homophobic jokes and one person pretended to punch another student. Considering these challenges, it may be more appropriate for younger students or students new to classroom argumentation to begin by discussing less divisive topics and to gradually move toward more sensitive issues. Citizenship education scholar Samuelsson (2016) explains that 'with highly controversial topics, students might be very emotionally attached to one specific position … and might be mainly interested in getting their points across. These aspects … could present challenges for creating the desired communicative pattern of reason giving, reflection, and collective-will formation' (p. 7). Instead, he recommends building argumentative skills first before introducing more polarising questions.

Yet, for students to practise genuine argumentation, they must feel some of the emotional involvement that comes with tackling controversial issues. Everyday matters that evoke little disagreement hardly make for compelling argumentation. So, how can teachers get students excited about cooperative argumentation without excessive risk of polarising them? A promising avenue may be found in philosophy. Proponents of the model known as Philosophy for/with Children (P4wC) claim that philosophical questions have the power to fascinate children and to invite them to explore divergent perspectives through dialogue, while adhering to an ethos of collaboration and playfulness (Fletcher, 2020; Lipman, 2003). Because philosophical questions are more abstract than political ones, yet no less fundamental, they can elicit just the right amount of personal involvement and controversy for children to discover cooperative argumentation without alienating one another. Indeed, empirical research suggests that children who practise philosophical dialogue become more comfortable with disagreement and more curious about others' opinions (Reznitskaya and Glina, 2013; Roucau, 2022). Nurturing a fallibilist disposition is another key goal of P4wC, which encourages children to be 'epistemically flexible' when involved in the give and take of dialogue, and to self-correct when warranted (Fletcher, 2020).

Further, the *content* of philosophy usefully complements its procedures. Many P4wC practitioners have adapted concepts from epistemology and the philosophy of science to develop educational resources introducing key aspects of science epistemology to primary and secondary students (e.g., de Schrijver and Cornelissen, 2016; Sprod, 2014). Empirical studies of these science-based philosophy dialogues suggest that they can increase students' conceptual understanding (Calvert et al., 2017), ability to cope with uncertainty (de Schrijver, 2017), and grasp of the nature of science (Dunlop and de Schrijver, 2020). P4wC's potential to cultivate young people's deliberative disposition is clear (Burgh, 2014; Nishiyama, 2022). We believe it also holds the potential to foster the fallibilist aspect of this disposition and to inculcate the fundamentals of science epistemology, thus making it an especially suitable pedagogy to educate young people for science and democracy.

CONCLUSION

In this chapter we have drawn a correspondence between fallibilist science and deliberative democracy, using both the scientific and political philosophy of Karl Popper as a broad framework. For theorists of 'deliberative democracy', democracy is as much about fostering rational and reasonable discussions as it is about observing a certain set of electoral procedures. The recent focus on the 'epistemic' aspect of democratic and republican systems (that is, their quality as systems conducing to public *knowledge*) opens up obvious parallels between democratic political cultures and science. We think Popper's ideas about falsification provide an especially helpful framework for thinking about this: just as scientists seek to falsify hypotheses one by one, democratic cultures test policies, on a piecemeal basis, against an ever-shifting background of available knowledge and popular preferences.

Without wanting to over-interpret the implications of Popper's work for education, we think that inculcating fallibilist dispositions in children is a promising approach to preparing the ground for both scientific thinking and democratic citizenship. We have suggested that P4wC is an excellent vehicle for doing this. Fallibilism is, in many ways, a counter-intuitive stance, whether it is deployed in a scientific or democratic context. For that reason, a likely challenge with taking a purely intellectual approach to teaching it will be managing students' cognitive load. This is especially so if it is included within science investigation, which presents pedagogical complexities of its own. On the other hand, if fallibilism is taught in the abstract, it is likely to be learned only superficially by many students.

One of the great advantages of P4wC is that it is participatory, affording young people a direct experience of argumentative deliberation. Such experience increases the likelihood of fallibilism being acquired as a disposition rather than just as set of theoretical precepts. The former is more likely than the latter to be prophylactic against cognitive biases, and to establish a robust intellectual culture among young people. In addition to being an excellent preparation for later participation in science and democracy, a fallibilist disposition may well, therefore, have positive implications for young people's psychological resilience more generally.

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