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Chapter 1

LUMPING AND SPLITTING IN CURRICULUM DESIGN: CURRICULUM INTEGRATION VERSUS DISCIPLINARY SPECIALISM

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ABSTRACT

This chapter considers how the school curriculum should be organised in terms of subjects, and, in particular, considers the relative merits of seeking to integrate different traditional areas of knowledge rather than organising the curriculum to reflect disciplinary structures. In many national contexts, school curriculum has traditionally been organised around subjects such as mathematics, language(s), science, history, and so forth. However, there has been much variation in the precise range and demarcation of these subjects, including attempts to organise new school subjects by combining cognate areas of knowledge, as for example integrated humanities. There have been shifts between ‘separate’, ‘co-ordinated’, and ‘integrated’ approaches to teaching the sciences, and attempts to subsume science, with technology and mathematics, under the

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'STEM umbrella' (and even extend this to incorporate others areas, such as the creative arts). Some science courses seek to teach through contexts considered to engage learners (e.g., food, textiles, transport), rather than in terms of traditional academic topics (such as digestion, acids, electromagnetism), and indeed there have been approaches to collapsing the full school curriculum and employing topic based-learning that draw upon diverse areas of knowledge on a 'need-to-know' basis. This issue is explored here in terms of a number of themes, including the purposes of education (which provide the rationale for constructing a curriculum), child and adolescent development, learning theories, the structure of disciplinary knowledge, and the supply and development of teachers. This analysis is applied to the example of 'the science curriculum' to suggest how judgements should be reached about how and when the science disciplines should be lumped together or split into discrete school subjects.

Keywords: school curriculum, school subjects, academic disciplines, curriculum integration, teaching science, STEM subjects, science and values, science for citizenship

INTRODUCTION

There are inherent tensions in designing curriculum. One of these concerns the tension between conservative and progressive tendencies. Part of the purpose of schooling is to induct young people into society, that is, into the traditions and norms of that society. To the extent that we believe that we live in a fair and decent society embracing institutions that are democratic and which protect and nurture all members of society, we might wish schools to reflect that society, and support education as a means to reproduce society. However, to the extent that we may feel that society falls short of our ideals - perhaps with institutions that maintain inequalities, we might prefer a critical approach to education, and seek a curriculum that can help to challenge, rather than maintain, the status quo.

This is an incredibly important matter because the status quo tends by its nature to be the default condition, and because institutions (both those formally established and codified in legislation, and those other informal cultural institutions that grow organically) can operate in insidious ways. This is not only true in dystopian Orwellian societies that are recognised as oppressive. Even in societies with long-held and much valued democratic traditions, which espouse social justice and toleration, there is a taken-for-granted background to everyday life which is subconsciously assumed and not readily even noticed (Schutz & Luckmann, 1973). This ‘truth’ is reflected in the joke about the two young fish swimming along who pass an older, wiser fish. The older fish says ‘good morning to you, what’s the water like today’. The young fish mumble politely back, and swim on. A little further on one of the young fish turns to his companion and asks: ‘what is water?’

Incommensurable Worldviews

This is reflected in different areas of scholarship. So, for example, Geertz (1973/2000) has noted how it is the very nature of being human to be encultured - that a human formed without culture is an oxymoron. Kuhn has used the notion of incommensurability (T. S. Kuhn, 1970) to argue how it is not possible to find an objective, neutral position from which to compare two worldviews. The notion of incommensurability derived from mathematics, when comparing - for example - the diameter and circumference of a circle (T. S. Kuhn, 1976/2000). The diameter and circumference can be compared, but are incommensurable in the sense that any kind of measuring stick which readily offers a length for one, will not do the same for the other. (The diameter and circumference are of course related by π, which is an irrational number, so if the diameter of a circle can be given as a definite multiple of any given unit, the circumference cannot, and vice versa.)

In the same way, Kuhn argues that it is not possible to fully understand beliefs from earlier historical times - such as the geocentric universe, or the use of phlogiston theory in chemistry - from our current standpoint, and nor is it possible to find some value-neutral position (cf. Geertz) from which to objectively compare two such theoretical systems (such as phlogiston theory and the ‘new’ chemistry developed by the Lavoisiers). When we look back at long abandoned scientific schemes (such as phlogiston) we may find it difficult to understand why so many intelligent and rational people seem to have adopted what seem to us such flawed and inadequate theories - because the sets of background assumptions which we take for granted and those which they took for granted are so different. We may be able to overcome our biases and learn to see the world in the ways of the other (which Kuhn feels is largely a kind of language learning, even when we are dealing with people who nominally speak the 'same' language), as historians and ethnographers, and indeed some researchers into students' scientific thinking, have shown - but this requires immersion and considerable effort to step back from what we take for granted.

Teachers as Conservatives

Teachers are perhaps guiltier than most. Indeed it has been said that "the only group more conservative than teachers is their students" (Parslow, 2012, p. 337). Most school teachers are, in our experience, decent people who (even if not without self-interest) work in education for the good of society to support the development of the young, and commonly tend to be concerned about issues that might be seen as progressive: environmental issues, issues of equity and rights, fairness, toleration, and so forth. On the other hand, teachers tend to be well inducted into the norms of schools and formal education systems, and the taken-for-granted assumptions that they reflect - teachers have usually both *done well at* school, and *done well out of* the existing school system.

So, on the whole, new teachers tend to be happy to go along with the status quo, much of which they may not even notice is just one alternative among several. Of course (a teacher would think) children must work alone when completing tests. Of course, homework is a positive thing. Of course, setting students according to ability is more effective than mixed ability teaching. Of course, it is valuable to learn about the periodic table, Newton's laws, and Shakespeare's sonnets. It is not that new teachers always reflect deeply about these matters, and after some deliberation come to these conclusions - rather they are often part of the background of taken-for-granted assumptions they bring to their preparation for teaching, and which their early experiences in schools as teachers do nothing to challenge. Preparation for ('training'), and induction into, teaching may be the most demanding and intense learning challenge that many new entrants have experienced, and the background of taken-for-granted assumptions about the nature and rituals of schooling may even provide crucial psychological support by anchoring the demands of teaching within a familiar milieu.

Teachers tend to welcome the official introduction of more progressive ideas in education, and readily adopt the language of innovations. Yet, this is often little more than 'pedagogic doublethink' (Taber, 2018b), as - in some contexts we are familiar with at least - it is in 'the back of the mind' that the innovation will never be fully resourced, and obviously (sic) the policy does imply fundamental change. ('Obviously', as it is taken-for-granted that, as Paul Simon has pointed out, "after changes upon changes, we are more or less the same".) So, for example, teachers can adopt the nomenclature of constructivist teaching knowing that as long as that veneer is in place and 'the talk is talked', and the school policy documents present the expected magical terms conspicuously, then we can all carry on with business (much) as usual. As long as the fashionable incantations are ritually expressed - be they 'differentiation', 'well-paced lessons', 'dialogic learning', or 'meeting the needs of the gifted' - the spell need not be broken.

The Curriculum as a Collection of School Subjects

Perhaps one of the most insidious taken-for-granted norms in schools in most contexts is the subject-based school curriculum. The school curriculum is composed of subjects. Indeed, as far as many people are concerned, the school curriculum is synonymous with a list of subjects. 'School subjects' are what get taught in schools. Subjects may be identified with academic disciplines, so (it may be taken-for-granted) school geography is geography; school mathematics is mathematics; school physics is physics; and so forth. The implicit starting point for designing the school subject is then the academic discipline. So, although many decisions need to be made, the ‘degrees of freedom’ available in making those choices are constrained,

> In constructing a curriculum, there are issues of selection and simplification. There is a need to decide what is included, and the level of treatment to be covered. Selection may be understood at two levels – deciding what falls under the remit of the subject of the course being taught, and then deciding what specific material should be included. (Taber, 2019b, p. 200)

Even accepting that this identify is subject to some necessary selection and simplification, it is still considered that, for example, school chemistry is essentially chemistry, even if somewhat like the free or discounted student version of some commercial software which omits some of the functionality of the expensive ‘professional’ package. We consider this ‘school subject as cut-down academic discipline’ identity is a norm widely taken for granted by students, their parents, the public generally, and indeed teachers; although, we suggest, it is an identity that invites more critical engagement.

This norm links to a second major tension in the curriculum, and that is the tension between a top-down and bottom-up perspective on curriculum. Should we be designing curriculum from the viewpoint of the learner, or from the viewpoint of the disciplines. That is to say, does it make more sense to think about curriculum primarily in terms of (a) the mature state of academic disciplines as these have evolved historically, and as currently established in academia; or (b) the current (immature) state of leaners’ knowledge, understanding and cognitive skills, the interests that might motivate them, and the pool of experiences they have as a resource-base to make sense of new learning?

We are not suggesting this is posed as a binary: as an all or nothing choice. Rather, something of both might be indicated. However, we suggest that when the question is posed in the terms we have just set out in the previous paragraph it would be perverse for anyone working in education to seriously suggest that the successful education of the masses is likely to have better outcomes if our starting point is the current state of the academy rather than the current states of the learners. And, we would quickly point out, the current states of the learners clearly means something different when those learners are five-year-old children entering school for the first time, eleven-year-olds transferring to secondary schools, or seventeen-year-olds on elective courses studying for university entrance examinations.

WHAT IS IT IMPORTANT TO LEARN?

A good starting point in thinking about school curriculum is what it is we might most want the young of society to learn about, and, indeed, to learn. One response might be along the lines of characteristics such as kindness, tolerance, empathy, gentleness, self-discipline, and the like. Now, two possible objections to such curricular aims might be, firstly, that such characteristics are personality traits which could be largely under genetic rather than environmental control; and secondly that, in any case, these are things to be taught in the home, not in school.

The first argument seems largely speculative, but without getting into the controversies of ‘nature’ versus ‘nurture’ in any depth, we would note that it seems pretty clear that the ‘versus’ debate here is hollow - that no matter how influential genes, environment also matters. To ignore environmental factors, then, is akin to the obese person who, being concerned about their weight, follows a strict diet during daylight hours, because they are aware what you eat when the sun is up affects your weight - but feels that this then justifies overindulgence after sunset. If environment has some effect (even if seen as an ‘interaction’ with genetics) then the school environment will influence character development.

The Centrality of Values

The second argument certainly has potentially more merit - there might reasonably be seen as some division in responsibilities between home and school, and some limit on the legitimate realm of school (i.e., societal) influence. Yet, is it not important that even when the ‘right’ values are taught within the home these must be seen to be reinforced outside? Moreover, as always in a democratic society, we run into the paradox of wishing to allow others to have freedom to be different from us - but not so different that they reject those values that we take to be fundamental, even essential, to the kind of society we wish to live in (such as wishing to allow others to have the freedom to be different).

We might think that if a parent that wished to bring up a son to believe that he should have dominion and control over a wife, and that if he could afford to acquire slaves, then deciding whether to do so should just be an economic calculation (how much would it cost, what benefit would there be?), then we would wish school to have a countering influence. If that seems a little fanciful, there is no doubting that not only are sexist, and indeed racist, beliefs common, but there is recognised to be much modern slavery out-of-sight - of course, as those subject to it have neither the physical freedom nor the psychological power to be visible (Bales, 2002) - in some of the supposedly most advanced, democratic, nations.

Schools therefore have dual roles, reinforcing those values society encourages for those from (we shall use the term, if in ‘scare quotes’) ‘good homes’, whilst challenging the assumptions children may bring to school from families that do not share these values. (Of course, that leaves open the very question of which values are considered ‘consensual’, or values of a ‘moral majority’, and there will no doubt be some obvious candidates, and some more debatable ones - setting out an account of which values schools should be espousing is outside the remit of this chapter.)

A more nuanced question is how this relates to curriculum. One response may be that, of course, schools should exemplify values, and it will do this in a wide variety of ways (by teachers showing respect for pupils, and expecting the same back; by teachers always being honest with pupils, and expecting the same back; etc.) but outside of the formal curriculum. This will be part of what has been called a hidden curriculum (Lempp & Seale, 2004): but not the explicit curriculum, which (it is taken for granted) will be made up of school subjects.

Our core focus in this chapter will be ways of understanding and organising the science curriculum, which provides a rich case study. This discussion of values may seem something of a diversion in an essay about science in the curriculum: after all, science may often be seen to be value-neutral. Even if we are looking to teach values in the formal school curriculum, within the school curriculum subjects, it might be argued that science lessons should teach about the natural world - and values are for the humanities. We would reject such a suggestion, partly because science is itself a value-based activity (aspirational values in relation to seeking truth, objectivity, openness, self-critique, weighing evidence above authority, and so forth), but mainly because there is a strong argument (discussed below) that an authentic science education must engage learners with socio-scientific issues that can only be addressed by considering scientific knowledge in conjunction with different value positions espoused when science is applied in the wider society.

Education for Society?

Another line of attack for our question is that we want young people to learn what is needed for them to contribute economically to society: we want to provide them with the basis for seeking employment. Whilst, perhaps, not the noblest educational aim, it is certainly an important one. But what will young people need to know, and to be able to do, to be employable and employed in the future?

The more senior author was at school at a time when many young people (these were almost exclusively young women) stayed on at school to learn skills such as shorthand and typing. Later the same author worked in a college of further education where there was a whole department teaching such ‘secretarial and office skills’ to young (and again, at that time, nearly always female) students. It is within living memory then that a young person who had a high speed and good accuracy in shorthand and typing could expect to be employable for life: every office had a pool of office assistants (informally, if inaccurately, known as ‘secretaries’) taking dictation and typing-up letters and other documents. As readers will appreciate, this role has virtually disappeared. Offices still sometimes needs to produce bespoke letters - but few clerks expect someone else to help them do the typing, and in any case much of the everyday business correspondence is completed (more accurately and quickly) by automated systems.

Perhaps accurate typing skills should still be formally taught, but to all, not just those taking up office work. Yet, one does wonder if in 20 years it will only be mavericks who insist on using a keyboard to compose text. If one was looking for a skill set today that was likely to assure vocational success one might guess at programming skills, and indeed it is increasingly recognised that schools should teach this aspect of computing (Moreno-León, Robles, & Román-González, 2016). Yet, even here, it is not clear that anything taught today will be directly useful in the job market in 20 years. Surely, if there is one area where work that is done ‘manually’ will be increasingly automated it is in relation to computers and IT. People can now tell their televisions which programme to display, so how long before we can tell computers what we need programmed?

These examples could be multiplied many times, but suffice to make the general point. It is very hard to see what specific skills that can be learnt in school are going to be directly useful for 40 years of productive work. In science there are many skills that might have once been part of practical courses - using graduated pipettes for example - that are now usually automated in industry: just as virtually no one today would use log tables or a slide rule to carry out a scientific calculation. Indeed, one of the authors - who *was* taught to use log tables and slide rules in school - remembers the slow acceptance of using calculators in school examinations against the counter-argument that this avoided the important skill of employing log tables to complete calculations.

Where Do We Teach Transferable Skills?

Of course, there are some generic skills that will, surely, never be outdated. We might think of communication skills, group-work skills (and perhaps increasingly, virtual-group-working skills), interpersonal skills, metacognitive skills… These are very important, and seem likely to remain so. However, it also seems pretty obvious that they are somewhat content-neutral: their development depends upon the kinds of learning activities students are assigned, and there is a myriad of potential contexts where such activities might be located.

So, for example, the ability of science education to support the development of critical thinking does not depend upon whether the curriculum includes study of molluscs, transformers or the halogens - but whether the learning activities that students undertake give them opportunities to engage critically with knowledge. It is the kind of thinking encouraged, not the subject matter thought about, that is critical (sic) here. A devil's advocate might argue that teaching literature can be more valuable in this context because (when taught well) this involves seeking and evaluating different interpretations, whereas science education has too often involved the presentation of a rhetoric of conclusions (Niaz & Rodriguez, 2000; Schwab, 1958) - a rational reconstruction divorced of all the argumentation which is so fundamental to scientific practice (Erduran, 2019). That is, too often school science has been akin to a presentation of history that offers a single narrative of fact and dates, failing to offer any sense that history is actually, necessarily, an interpretive activity (Gardner, 2010). Any authentic history education has a flavour of enquiry, rather than simply fact-acquisition - and the same must be true for an authentic science education.

Education to Support Student Aspirations?

Now a reader might make a very good point that this analysis has so far ignored something rather important about our young people's success in entering a field. If we imagine our student wishes to become a research scientist, or an engineer, or a medical doctor, then they will need to gain entrance to university courses, which will require passing school science examinations with good scores. So, in practice, someone who does not understand Newton's laws, who does not know the difference between ionic and covalent bonding, who cannot explain how the four chambers of the mammalian heart support blood oxygenation and circulation, and so forth, will not do well in terminal school science examinations and so will likely be unable to enter their chosen profession. This is a fair point. However, we would argue, that this is how things are (the status quo, the taken-for-granted) and need not be the case.

That is not to say we would not wish such things to be taught in school, but just that it is quite likely much of what is specified in school science courses could be removed (if it was not tested in the terminal examinations) and could then be readily acquired on undergraduate courses if need be. This is not an argument for a content-free science curriculum - but just a comment that as science teachers we too easily think (i.e., take for granted) ‘they need to know THAT’ when most of the students will get by in life pretty well without doing so, and any that might find it useful could easily learn about it later. There is a virtual infinity of things that could be taught in science classes, nearly all of them could conceivably be useful to some students one day, but most of them could be lost without doing any more than mildly inconveniencing the few who later find they had good reason to learn the topic. Perhaps as part of science teacher education, all candidates should be asked to undertake a comparative study of school science curricula across different national contexts to see that what is taken for granted as essential or desired can vary considerably (see for example, Comparing the national standards of various countries, below).

An Authentic Science Education Engages with, But Should not Be Primarily Defined in Terms of, Science Content

As one example: consider a student of biology had demonstrated that she was capable of learning about the functions of the kidney, and how the kidneys worked as part of a larger system, and how the structure of the kidney supported (and inherently in some senses limited) kidney function, and about the role of the kidneys in homeostasis, and so forth, yet this student had not been taught anything about the liver because it was not specified in their particular course. Would it not be reasonable to assume this student had demonstrated the potential to learn about the liver when the need arose - assuming of course this student had learnt good study skills (thus our earlier reference to metacognition as an essential area among generic skills important for all students).

Chemistry teachers of a certain vintage may be nodding wisely here: many years ago it was decided in some national contexts that rather than expect senior school students to complete a survey of the properties, trends and reactions of all the main groups of the periodic table (as had sometimes been custom and practice), it would suffice to learn about just a couple of the groups given that the overarching principles at work could be learnt equally well from a few examples, and that, once these general principles were acquired, the specifics could readily be discovered (if ever needed) from a standard text. This would allow more time to focus on understanding and applying principles, rather than seeking to cover a vast amount of material.

Education for Cognitive Development

It can be argued that part of what education needs to support - and perhaps science education is especially valuable here - is not so much conceptual development (the understanding of particular abstract concepts), but cognitive development - the acquisition of higher-level thinking skills: those intellectual skills that support problem-solving (and indeed problem identification and characterisation), critical thinking, and creative thinking. We do think that this is a very important purpose of education, and that science education has very important role to play in this regard.

The way in which curriculum responds to this imperative is less about specific content than about the way student learning activity is organised. There will still be a need to select some science content as the context for learning, but more of the focus should be on the transferable skills to be learnt and the opportunities to encourage cognitive development, than on the acquisition of specific details of a wide range of science topics. Most practising scientists never have reason to use much of the science they learnt at school in their professional work, but they all use skills of critical thinking, logical analysis, collaboration, clear communication, planning-ahead and scheduling activity, and so forth.

Of course, science teachers will (rightly) ague that science helps us understand the world, and there are many fascinating topics that can be taught. This is certainly so, but if we want students to find those topics fascinating we need to offer them sufficient engagement to master the complex ideas and to feel that they can really apply the key principles. That means being selective about topics: as the science curriculum as a quick-survey-of-as-many-science-topics-as-possible (as has sometimes been the case) is too often experienced as a confusing blur - and anything but fascinating (Cerini, Murray, & Reiss, 2003; Osborne & Collins, 2000).

This argument reflects theoretical perspectives on intellectual development. For example, in the work of Piaget (1970/1972) the learner interacts with the environment and this supports the development of new cognitive structures. The development of formal operations requires engagement in a certain kind of thinking. Research suggests that this process can be ‘accelerated’ by providing the right kind of learning experiences (Adey & Shayer, 1994), and that science and mathematics in particular can offer the kinds of contexts that support these experiences. The abstract nature of many scientific concepts and the type of activities needed to investigate these concepts lend themselves to supporting cognitive development. Within science, there are a great many potential contexts that could be employed for this purpose.

Similarly, Vygotsky’s (1978) model of learning and development suggests certain types of activity are likely to support the development of higher-level intellectual skills, and again scientific contexts can provide opportunities for the kinds of activities expected to be productive (Taber, In press-b). And, again, there is a choice from a wide range of science concept areas that could be employed. From this perspective, it is less important what science is being taught, than how it is being taught. Rote learning of complex lecture notes on a highly abstract science topic is unlikely, of itself, to promote conceptual development any more than it is likely to promote enthusiasm for the subject matter.

Whilst Vygotsky's schemes may be judged as theoretical, his fundamental assumption, that ways of thinking that are taken for granted among human adults in modern literate societies may be dependent upon education and so do not develop spontaneously without particular kinds of cultural mediation, gained support from his colleague Luria's (1976) fieldwork in societies in Asia that were only then being 'modernised' as part of the Soviet Union project. (Whilst this work has to be seen as subject to some ideological bias, and is open to various criticisms, it responded to a unique natural experiment and offered insights from contexts within societies in transition that are not readily studied.)

Another important theorist is Perry (1985) who's scheme of intellectual and moral development conflated what had been termed the cognitive and affective domains (Taber, 2015) by considering the fundamental cognitive processes that support the development of a coherent system of personal values, to be common with those that are responsible for developing the reasoning skills valued in disciplines such as physics or mathematics. Although Perry's scheme was developed in a somewhat normative fashion by seeking to describe the stage of development of undergraduates (the qualification 'somewhat' seems justified given these students were from elite colleges), he also noted how the average level at which students were admitted to degree courses seemed to have changed over time in a way that was correlated with increased sophistication of the tasks set in examinations - that is, changes in a key feature of the environment, education, seemed to have accelerated the intellectual development of young people. Although Perry's evidence was somewhat anecdotal, it seems consistent with the way outcomes on IQ tests had been found to improve substantially during the twentieth century (Flynn, 1987).

Now Perry's work offers an interesting complement to that of Piaget, which also offered a kind of normative model of development of the 'every-person' epistemic subject, when considering implications for science curriculum. Piaget's highest level of cognitive development, formal operations, is both facilitated by experience with the abstract nature of, and ways of representing, scientific modes of thinking - and is also necessary for the lone epistemic subject to successfully engage in that type of thinking. If that seems something of a paradox (a version of the learning paradox, i.e., that development was supported by experience that only becomes possible after that development has occurred), the successful programme of conceptual acceleration referred to above was not only informed by Piagetian stage theory, but also Vygostky's notions of how such development could be mediated by working with others (Adey, 1999).

Cognitive Development Beyond Formal Operations

In Piaget's scheme the highest level of cognitive development allows a person the carry out mental operations on mental representations - that is, not only abstracting from phenomena to form mental representations, but then to be able to mentipulate (e.g., do thought experiments on, and with), those mental representations. However, it is assumed that these operations will be logico-mathematical. So, as an example, a person might form a theoretical concept to explain some phenomenon; be able to deduce a testable hypothesis that is entailed by the theory; imagine how an empirical test of the hypothesis could be carried out; and then consider the logical range of potential outcomes of that test, and determine which outcome(s) should be considered to support, or throw doubt upon, the hypothesis and, consequently, on the theoretical construction.

This is indeed an impressive competence for a mature human to acquire when we consider what is possible for the neonate. However, some commentators have suggested that this is not the highest level of cognitive development people need or reach (Arlin, 1975; Kramer, 1983; Sternberg, 2009). It can explain problem-solving, but perhaps not problem identification; it can explain how we make decisions logically when we have sufficient data, but not how we proceed rationally when there is insufficient data for a definitively justifiable decision, or when we have to balance multiple opposing considerations that are incommensurable.

As one example, questions about siting power plants, industrial complexes or airports may have clear economic cases - but there may also be aesthetic considerations - or environmental costs which cannot be simply represented in monetary terms. How much additional economic cost is it appropriate to incur to avoid losing a vista that the local people consider a beauty spot? Of course, there is no 'right' answer to such questions as it is matter of applying a set of personal values. This is where Perry discovered many young people struggle in their educational careers. A learner used to having been set tasks where there is a preferred answer (a single 'right' answer), then meeting situations where the teacher cannot tell you what the 'right' answer was meant to be, may experience a shift to relativism - that is, the view that it is all a matter of opinion or taste, and one person's preference is as good as another's (Taber, In Press-a). Over time, a student may pass through such a relativist stage to build up their personal value system, which would support them in making choices which they appreciate could not be seen as objectively or universally 'right' but which they could nonetheless commit to and justify.

Traditionally school science has been very good at offering experiences that can support (and indeed require) formal operational thinking: tasks working with conceptual schemas and mathematical analysis and leading to definitive answers. But, if we take the work of Perry and others (e.g., D. Kuhn, 1999) seriously, such a science education is leaving engagement with the highest stages of intellectual development to other curriculum subjects (considering issues such as the relative merits of Beethoven or Brahms; or of Tolstoy or Hardy?; should Nietzsche's philosophy be considered fascist?; how might the French revolution have developed had Louis XVI been in more robust mental health?…).

Science Curriculum for Promoting Intellectual Development

Such a judgement reflects a particular traditional vision of the science curriculum - perhaps even an often taken-for-granted vision: science has provided us with definitive, straightforward answers that can be readily applied through technology. Yet, there are different notions of what should appear in the science curriculum. There have been strong recommendations that the science curriculum should include much more emphasis on the nature of science (Clough, 2017; Hodson, 2014; Taber, 2016b) and socio-scientific issues (Levinson, 2007; Sadler, 2011).

The nature of science offers perspectives that can undermine some of the apparent objective certainty about science. For example, all theories may be considered under-determined. That is, no matter how much data is collected, and no matter how well that data appears to fit a theory under consideration, it is always possible to construct another theory which would also be consistent with the data. Thus, choice between theories is never purely down to the available data. (So here scientific values may be invoked: preferences for simplicity, symmetry, elegance, potential to integrate disparate material under a common scheme, and so forth.)

Another principle is that all experiments are actually tests of compounds of the hypothesis that it is intended to test plus the assumptions built into the instrumentation used to collect and analyse data (perhaps the metre rule is not precise, perhaps the small angle approximation does not apply in this case, perhaps the method of preparing samples for examination under the electron microscope changes the structures being examined; perhaps the computer simulation of the degradation of the particle detector is not accurate…).

Another pertinent principle is how all observation is necessarily theory-laden. It is never possible to adopt a totally neutral viewpoint as this would be to revert to experiencing the world as a ‘blooming, buzzing confusion’ à la William James (1890). (Just as this is true in anthropology or history, see above, it is also true in science.) Deductions from experiments assume we have identified and can control all the variables pertinent to a particular test - but there are well-described examples where anomalies have been investigated and found to be due to some variable that was not controlled because it was not imagined to have conceivably had any relevance (Alger, 2020) - such as the sex of the scientist handling animals used as test subjects.

Whilst it could be felt that introducing such complications into school science could risk undermining student faith in science, arguably science teachers should not be asking students to believe in scientific theories and models in the first place, but rather to understand them, and appreciate the grounds on which they are entertained (Taber, 2016a). This means appreciating both strengths and limitations of the theories that are taught in school science.

Education for Citizenship

Moreover, if science education is to support preparation for citizenship in democratic societies that take scientific evidence seriously, then young people have to both (i) appreciate the strengths and limitations of science in order to make sense of the science, and (ii) be able to maintain a critical attitude to reports of science in the media when engaging in the kinds of everyday political action important for civic engagement (voting, joining or supporting pressure groups, making consumer choices, adopting recycling and other ‘sustainable’ behaviour, and so forth).

A similar argument can be made about including socio-scientific issues in the science curriculum. Only a small proportion of school children will go on to engage in professional activity as scientists where they will be asked to think like researchers. But most people will be faced with decisions about healthcare and medical treatment for themselves or their families. This might be in relation to fairly trivial issues: should one pay more for dental fillings that match natural tooth colour but are technically no better than amalgam fillings? Yet, often, it may concern much more serious matters: should a person with terminal cancer undertake chemotherapy that will likely extend their life by a few months if that requires frequent attendance at the clinic and has serious side effects which reduce quality of life in the meantime?

There are clearly no right or wrong answers to such questions. Whether you value the more ‘natural’ looking fillings might depend upon various non-scientific factors (how much expendable income do you have? are you looking for a romantic partner? is the tooth visible whenever you smile or only under close, intrusive, inspection?) Whether extra time alive is seen as more important than comfort in the meantime is a personal decision that may be impacted by idiosyncratic considerations (e.g., would a few more months mean you will likely live long enough to see your first grand-child?; will it give you time to finish writing that magnum opus?; would rejecting the therapy allow you to go on that trip to Florence that you always intended to take?)

Socio-scientific issues relate to scientific topics and draw upon scientific ideas and data (how robust are different dental filling materials; how much is it expected this medical treatment would typically extend the life of someone with this kind of tumour when it is this far advanced?) but are matters that cannot be decided based upon the scientific evidence alone as extra-scientific values need to be considered as well (Sadler, 2011). A person who has a strong personal, perhaps religious, conviction that life is so precious it should be extended whenever possible and another person who has a strong personal, again perhaps religious, belief that a ‘natural’ life with minimal medical intervention is inherently of higher quality and value than medicated experience, may make very different choices given the same scientific understanding and data. Moreover, these would *both* be rational decisions given the extra-scientific considerations.

A science education that only concerns the science, and not questions of its application (in relation to such matters as weapon technology as well as in areas such as agriculture and medicine) and limits itself to the logical, and ignores the ethical, or indeed the aesthetic, does not prepare people for the kinds of science-related decisions they are likely to face in adult life. Moreover, a science education that includes engagement with socio-scientific issues not only provides experience of navigating this kind of scenario, but also supports development towards the kinds of post-formal thinking that reflects the highest levels of intellectual development (Taber, 2016b).

A Liberal Curriculum for Holistic Development

Before turning to consider how the science curriculum might be organised, we examine one other perspective on curriculum, this is the idea that schooling supports the development of the whole person by introducing the young to the different forms of life that make up their culture. We might link this to notions of a liberal curriculum (Hirst, 1974) that supports aspiration to a good life, and to the European notion of education supporting Bildung (Hansen & Olson, 1996) as a holistic form of personal development. So, if literature, music, dance, fine arts, and so forth, are valued cultural activities, then they need to be included in schooling. The same goes for philosophy, or history, or science, and so forth.

That is, we do not expect everyone to be able to compose symphonies, write epic poems, publish philosophical treatises and discover new biochemical pathways in order to be considered fully members of the culture: but if someone left school never having listened to a symphony, never having been asked to think about some poetry, not having heard of Plato and Popper, and having no idea what the electromagnetic spectrum is, we might consider that schooling as deficient. (And we are writing this whilst based in a country where we suspect that a good many children may pass through formal schooling without being asked to listen to a symphony, or being told anything about the thought of Plato or Popper!) The precise things to be put into such a list is, of course, moot.

This raises the question of how culture is understood. Perhaps we are talking about high culture, but it still depends on what is meant. If by high culture one thinks of those elements of culture which have been valued over an extended time, and have taken their place in the canon, and so become institutionalised (whilst recognising that this needs to be a shifting canon with permeable borders), then that seems inherently a reasonable basis for making curriculum judgements. So, this might be high culture as in that which is influential and widely engaged with. We would be much less comfortable with a notion of high culture as being that of the elite (the ‘rich and powerful’) such that opera and ballet are in, reggae and ballroom are kept out. We are wary here, as clearly there is a potential for those with most influence to make judgements on behalf of everyone: judgements that can - either inadvertently, or perhaps deliberately (even if paternalistically) - decree what culture counts. Inevitably, it takes time for some œuvre or activity to be recognised as high culture, but it would seem very suspicious if the Beatles (certainly influential in popular music) or Ballroom dancing (certainly widely engaged with in performance, and especially as an entertainment) were not considered important aspects of British culture today. (This reflects permeability: it might be noted that two decades ago it would have been widely considered that ballroom dancing was no more than a passé and clique minority interest, and indeed perhaps an anachronism, whereas today it occupies prime-time Saturday evening television viewing.)

There are clearly important debates to be had there, but what does seem clear is that culture necessarily becomes institutionalised when it reaches a professional status. In particular this happens in the academy in terms of the disciplines. In one notion of a liberal education the role of the disciplines as frameworks for thinking about and planning curriculum is seen as central (Hirst, 1974), but even those who have never knowingly engaged with such considerations will often take-for-granted that the school curriculum needs to be organised by subjects, and that these will largely reflect the academic disciplines.

ACADEMIC DISCIPLINES

By their very nature, institutions tend to formalise, and protect and reproduce, aspects of a status quo. Academic disciplines have hierarchies. Those who are recognised as being the 'top' people in the field are asked about, and so have influence in such matters as, employment and promotions, publications, grants and awards (the very things that allowed those top people to themselves reach the top). There is therefore often a bias to those ways of doing things, and ways of thinking, that are adopted by those who are most senior in the field. We do not suggest bias is inherently a bad thing, and it need not imply prejudice. Judgements have to be informed from somewhere, and asking those with the greatest esteem in a field to bring their successful experience to bear as the basis for making judgements is a sensible policy, although it may tend to be a conservative one.

Disciplines develop traditions (T.S. Kuhn, 1970), and those traditions which are well-established and retained tend to be those which are judged most fruitful and productive (Lakatos, 1970). Yet, of course, they can also become taken-for-granted, and may be retained beyond the point where an original rationale no longer applies. There is much that could be said here on this theme, but we will offer just a few examples.

Contingent Disciplines

Firstly, it should be recognised that contingency plays a substantial role in the development of disciplines. Disciplines that are well-established develop identities, and to some extent boundaries around what is included, or not, within those disciplines. If we consider scientific disciplines such as chemistry, biology, physics, geology, astronomy, or so forth, then these are certainly not arbitrary traditions - random collections of topics and concepts. Yet it is also true that there is nothing inevitable about them. It would have been possible for a science to develop which covered much of the area that we think of as chemistry plus geology; or for physical chemistry to have developed as a part of physics and not been seen as chemistry at all, or for biochemistry, pharmacology, and physiology to have developed from within one unitary parent academic discipline.

As a thought experiment, we may think of other worlds much like our earth and subject to the same universal laws, and perhaps even with very similar geology and biota, where somewhat different ways of fragmenting science might have occurred. We can imagine one of these worlds has intelligent creatures that have their own version of the Academy. Perhaps in their culture, a version of alchemy was accepted as a respectable activity for natural philosophers, and their Newton openly (rather than covertly) worked in proto-chemistry as well as physics - and a unified physical science developed. This would clearly not make any difference to the chemical and physical phenomena this science engaged with, but discrete chemical and physical phenomena as such would not exist. Science may focus on natural phenomena, but is itself a social phenomenon.

Disciplines evolve - so fields grow and sometimes disappear, and new specialisms come into existence (T. S. Kuhn, 1991/2000) and some of these are at the boundaries between existing disciplines. Disciplinary boundaries are not then set in stone as they have a degree of permeability. Yet this permeability, and the associated plasticity of the identity, of a discipline is limited. And such changes never start from a *tabula rasa*: but rather an existing typology of sciences. The sociologist of education, Basil Bernstein, saw that this is reflected in schooling where subjects such as the sciences tend to have more rigid boundaries:

> There is always a boundary. It may vary in its explicitness, its visibility, its potential and in the manner of its transmission and acquisition. It may vary in terms of whose interest is promoted or privileged by the boundary…the issue is how is the boundary acquired. (Bernstein & Solomon, 1999, p. 273)

The references here to explicitness and visibility are interesting, for when students who have studied years of school physics, chemistry and biology are asked about the demarcation of these subjects they may only have the vaguest ideas of, for example, what makes a particular collection of topics 'physics' (Taber, 2014). Nonetheless, the implicit identity of physics, and the notion that it includes some topics but not others has become taken-for-granted.

The Insidious Influence of Custom and Practice

The philosopher Bachelard (1940/1968) considered that science retains ontological obstacles to progress in the form of how now anachronistic perspectives have been 'fossilised' within the way concepts are understood and are represented in texts (and so teaching). An extreme example is the concept of atom, where aspects of the notion of indivisible solid bodies still permeates popular perceptions and the school curriculum (Taber, 2003). This is akin to the way learners have such trouble overcoming some aspects of their alternative conceptions (Chi, 1992) - for example, in coming to think of circuits in terms of fields that act throughout the system rather than as linear chains of cause and effect. It is also seen in the way students struggle to move between models at different levels of study - for example moving from electron orbits to orbitals (Taber, 2005a). However, even mature 'experts' may fall back into classical ways of thinking when relativistic or quantum-mechanical patterns of thought are needed to make sense of phenomena according to current scientific models.

T. S. Kuhn (1970) described how the education of scientists involved paradigmatic induction into a disciplinary matrix that was largely a kind of intellectual apprenticeship, where much learning took place implicitly through exemplars; and how this could be a barrier to shifting our ways of thinking when that becomes appropriate. Lakatos (1970) described how science is organised through research programmes, each with its own set of taken-for-granted hard core assumptions, and a well-established positive heuristic guiding work. When working in such a tradition it is often sensible to 'quarantine' anomalies rather than abandon an established programme. We reiterate, we are not suggesting that such conservative tendencies are necessarily malign: scientific practice requires a certain degree of stability and so a high standard of evidence is a sensible requirement for overthrowing ideas or norms that have served well. Yet we note that once a way of doing things is well-established, it may easily become the taken-for-granted: it may be more obvious to ask why we should change something than to question why it should stay the same.

SCHOOL SCIENCE SUBJECTS - SPLITTING AND LUMPING

Typologies are models which put things into categories. Science involves the construction of typologies of natural things: types of star, types of rock, types of infectious disease, types of subatomic particle, and so forth. When we develop typologies, we have choices to make about the degree of differentiation we wish to represent. Perhaps the paradigm case of 'typologising' occurs in biology with taxonomy, where historically there have often been debates about the best ways of classifying organisms - for example distinguishing between when two very similar but slightly different specimens should be classed as different varieties of the same species, or actually different species. Ever since Darwin (1859/1968) it has been clear there are no absolutes in such matters: it is not a question of whether X and Y are, or are not, specimens of the same species, but whether they are best considered as such.

The terms ‘splitter’ and ‘lumper’ therefore refer to people who tend to prefer to either (respectively) focus on differences and populate more types, or focus on similarities and limit the number of groups populated. Arguably, the existence of scientists with different instincts in this regard is healthy as it ensures such decisions are subject to critique and debate, and Darwin is said to have considered that “it is good to have hair-splitters and lumpers” (Endersby, 2009). In the case of chemistry, for example, we might detect a ‘lumping’ tendency in how the definition of acid has shifted over time to give an increasingly more inclusive category (Taber, 2019c).

Conceptualising Science as a School Subject

This brings us to consider science in the school curriculum. If the school curriculum is composed of school subjects, then one option is that there should be a school subject called ‘science’ that collectively represents the different disciplines of natural science. However, this is clearly not the only possibility, as if there are distinct scientific disciplines, then an alternative is not to lump them altogether in one school subject called science, but rather to represent them in separate school subjects - so perhaps as separate timetable slots labelled as biology, chemistry, physics. However, this by no mean exhausts the possibilities.

So, considering the choice of a single curriculum subject of science, it is possible to organise this so that as far as the students are concerned it is a unitary subject - with different topics that are just considered ‘science’ topics. But it also possible to identify different disciplinary streams within the school subject, so that although the school timetable shows ‘science’ the learners are aware that at any time this particular science topic is part of, say, physics. In the former case it may be that the topics making up the science curriculum are largely recognised by the teachers as being ‘biology’ or ‘chemistry’ or ‘physics’ although this is not made explicit for the students.

However, it is also possible that topics are organised in ways that often move across those disciplinary boundaries - an approach sometimes called ‘integrated science’.

If separate sciences are taken as the named school subjects, then this need not be biology, chemistry and physics. Earth sciences (or more specifically, geology) could appear (or astronomy or electronics or…). Or the sciences could be divided, but into life and environmental science, and physical science. There are clearly many possibilities - and probably most we could suggest have been enacted at some time or other (see Comparing the national standards of various countries, below, for some current practices).

However, it is also possible that the school subject(s) could ‘lump’ differently. It used to be the case in England, before the introduction of a National Curriculum, for example, that schools could work with examination boards to develop examination subjects that were considered to be especially suited for particular groups of students (Misselbrook, 1972a) - such as rural studies for schools in rural settings where agriculture was a major economic activity. The senior author taught in a school where the higher achieving group of students were offered a subject labelled physics; but the average achieving groups were instead offered a physics-based examination course in ‘engineering science-applied science’, considered to be more engaging to that group of students; whilst another group of students took ‘engineering science - automotive science’ (which largely contextualised the science in terms of motor car maintenance).

A recent trend in many educational contexts is to consider ‘STEM’ as a curriculum area (Chesky & Wolfmeyer, 2015; Freeman, Marginson, & Tytler, 2015) that encompasses science, technology, engineering and mathematics - with various degrees of integration (Taber, 2018a). Whilst these areas are certainly ‘cognate’ to some degree, they are very different in nature (arguably much more so than integrated humanities). There have even been moves to include other subjects with STEM (Colucci-Gray, Burnard, Gray, & Cooke, 2019; Sumida, 2018).

Reflecting Student Development

A further consideration besides the ‘horizontal’ dimension of degree of clumping/splitting across disciplines is the ‘vertical’ dimension of learner development. This needs to reflect what learners are ready to learn, and has at least two distinct aspects. One is in terms of cognitive development - clearly what is suitable as curriculum for a child starting school is different to what is most suitable for a 17-year-old.

Therefore ‘science’ in the early years of schooling should act as a preparation for meeting, and not just be a watered-down version of, secondary school science. That is, the best preparation may need to focus more on enquiry skills, attitudes to and wonder in nature, and scientific values and attitudes, rather than particular knowledge (Taber, 2019b).

The other aspect of preparation reflects the constructivist principle that learning is interpretive, incremental and iterative (Taber, 2014), which suggests that (even leaving cognitive developmental level aside) the degree of complexity students can engage with evolves as learning progresses. A clear pattern one would expect, then, is that the curriculum experience will become more differentiated as the learner progresses through schooling.

The Demands on the Teacher

What this discussion has ignored to this point is that whatever is prescribed in the curriculum policy, it will only be the basis of student learning to the extent that teachers are able to effectively teach it. The more we clump disciplines into a single school subject, the broader the requirements for the teacher. If a coordinated approach is taken (the school subject is science, but within this teaching modules are based around topics from within the distinct science disciplines), specialist teachers can operate as a team within a single school subject (with the added timetabling complexities this involves) - but this increases the extent to which the teaching of ‘a’ subject (‘science’) could appear disjointed to the student.

If, on the other hand, one teacher is expected to teach across (and perhaps even beyond) the sciences, then we are expecting a wide breadth of expertise - with the knock-on consequences for teacher preparation and development. Even if we think that science learning is not primarily about topics and concept areas, but broader concerns such as enquiry skills, we still need to recognise that these are also differentiated to some degree across scientific disciplines. And, certainly, when we move to such umbrella subjects as 'STEM' we may be expecting teachers to model a range of disciplinary practices that no single disciplinary specialist would ever have to master.

What all this suggests is that, even when just focusing on science, there are a good many possibilities for how the discipline(s) may be represented in the structure of the school curriculum. Having considered a wide range of issues that impinge upon the decision about how to frame science in the school curriculum, we now turn to consider how curriculum authorities across a range of different educational contexts have attempted to 'square the circle'.

COMPARING THE NATIONAL STANDARDS ACROSS A RANGE OF COUNTRIES

The previous sections have argued that the goals for a science curriculum can be manifold. The Japanese Course of Study emphasises the cultivation of skills and knowledge to prepare students for proactive, independent learning in order to open the way for the future in a complicated, unpredictable world and cope with social changes such as globalisation, rapid ageing and very low birth rate (MEXT, 2017c). Similarly, the Brazilian Base Nacional Comum Curricular (BNCC, the common core curriculum) highlights the need to equip students with the capacity to exercise citizenship by being able to apply their scientific understanding, skills, attitudes and values in order to engage in discussions concerning a wide range of issues (MEC, 2017). In contrast, the Chinese national standard was constructed around the theme of enhancing students' scientific literacy. That includes four elements: 'scientific knowledge', 'scientific enquiry', 'scientific attitude' as well as 'science, technology, society and environment' (MOE, 2011, 2017a, 2017b). At high school level, each discipline also has its own disciplinary goals. For instance, the chemistry syllabus aims to develop 'chemical literacy' which includes themes: 'macroscopic identification and microscopic analysis', 'the concept of change and balance', 'evidence-based reasoning and modelling', 'scientific inquiry and creativity' and 'scientific attitude and social responsibility' (MOE, 2017a).

One way in which these curriculum standards achieve their aims is the creation of an integrated science curriculum, particularly at the primary level. The Chinese national standard notes that an integrated curriculum, one in which various scientific disciplines are combined as a single school subject, presents a holistic view of science and prepares students for solving 'real life' problems, which commonly requires utilising knowledge and methods drawn from several disciplines (MOE, 2017b). On the other hand, the Next Generation Science Standards (NGSS) from the United States suggest that an expert knowledge base develops better through establishing interdisciplinary connections, rather than working in isolated contexts (NGSS, 2013, Appendix G).

Sometimes an integrated curriculum brings together social and science studies to introduce students to various perspectives for understanding the world. Often themes such as environmental, social and health issues form an overarching nexus relating the materials in the separate scientific disciplines. Within so-called STEM education in English speaking countries there is a common trend for these standards to integrate science and technology education so that students appreciate the nature of the applications of science in the world. Many of the curricula are planned from a 'vertical' perspective, taking into account the cognitive development of the students (as discussed above). Hence in many countries, the primary curriculum is theme-based and concerns objects and phenomena in students' lives and disciplinary boundaries are then introduced at the secondary level.

Here we briefly review the science curriculum standards of a selection of countries: Brazil, China, Germany, Israel, Japan, Russia and the United

States. In reviewing these standards, several themes relating to the content chosen for integrating science curriculum and its arrangement emerge. They are: 1) environmental, social and health issues, 2) integration of science and technology, 3) core ideas, and 4) learning as progression. A brief discussion of these themes illustrates how different national standards can employ integration across content materials in science. An overview of curriculum content then describes how each country constructs its science curriculum.

Environmental, Social and Health Issues

Social, environmental and health issues are important themes in many national standards across grade levels. For instance, in the primary science curriculum in the Brazilian BNCC, when students learn about energy, they also learn about the history of human exploitation of energy resources, and electricity generation and its relationship with society and technology; while in the 'earth and universe' unit, students may study the greenhouse effect, how humans gain autonomy in agriculture, and the historical shift between heliocentric and geocentric models. In the 'life and evolution' theme, the characteristics of, and the importance of preserving, biodiversity; and the participation of humans in food chains, and as a modifying element of the environment; as well as sustainable habitats, may be discussed (MEC, 2017). There is also instruction about the idea of excessive consumption and the role of state policies (e.g., vaccination campaigns, research investment) in promoting individual and collective health (MEC, 2017).

Likewise, the Japanese Course of Study highlights the necessity for environmental conservation and encourages students to think about how to create a sustainable society through observations from everyday life, to the scale of society, along with other topics such as recycling, GPS, solar energy, natural disasters and their prevention, and the body clock (MEXT, 2017c). In the Brazilian BNCC, it is set out that for students to understand health in a comprehensive way, they not only need to understand the functioning of their own bodies, but also related topics such as basic sanitation, energy generation, and environmental impacts, as well as the use of medicine and its effects on the body (MEC, 2017).

Across the national standards of a range of countries (e.g., Israel, Japan, China and Brazil), within the discussion of these issues, there is also teaching about human values such as developing a loving and protective attitude towards nature, as well as the importance of ethics in conducting research.

Integration of Science and Technology

All of these countries also draw together the disciplinary traditions of science and technology within their curricula. In the NGSS (the United States), the learning of engineering design and scientific inquiry are combined as it is argued that this allows students to appreciate the important applications of science in everyday life; as science pursues understanding of the natural world, in part at least, to satisfy intellectual curiosity, whereas technology and engineering are means of accommodating human needs and aspirations (NGSS, 2013, Appendix F). Similarly, within the Chinese national standards, an important theme is ‘science, technology, society and the environment’ in which students learn about technology in everyday life, and how technology is changing the world and advancing the development of human society and civilisation (MOE, 2017b).

In Germany, an emphasis is put in the idea of MINT education (Mathematics, Informatics, Natural Sciences, Technology), which is popular in Europe and comparable to STEM in English speaking countries (EC, 2019b). Israeli curriculum policy takes the STS (science, technology, and society) approach which draws attention towards the cultivation of scientific and technological literacy. Based on a programme developed through the educational reforms in the 1990s, it presents students not only with facts, concepts, principles and theories in the science and technology areas, but also encourages them to understand the processes, the limitations, and the potential contributions of science and technology to society (Ministry of Education, 2016).

Core Ideas

Many national standards point out cross-disciplinary ideas as a way to develop relationships between the disciplinary ideas and facilitate the development of a coherent knowledge base. For the US, seven core ideas from science and engineering are selected: ‘patterns’, ‘cause and effect’, ‘scale, proportion, and quantity’, ‘systems and system models’, ‘energy and matter: flows, cycles and conservation’, ‘structure and function’ and ‘stability and change’ (NGSS, 2013, Appendix G).

Similar cross-domain ideas are also noted in the Israeli standards, and teachers are encouraged to explicitly reference them in lessons (Ministry of Education, 2016). They are: ‘patterns’, ‘models’, ‘systems’, ‘structure and function’, ‘size and ratio’, ‘cause and effect’, ‘stability and changes’, ‘materials and energy’ and ‘forces’ (Ministry of Education, 2016). For instance, the idea of ‘stability and changes’ is involved in understanding the feedback processes that maintain the thermoregulation system as well as the processes that provide homeostasis in living cells. In the Chinese curriculum, the core ideas in science are: ‘matter, motion and their influence on each other’, ‘energy’, ‘information’, ‘system, structure and function’, ‘evolution’, ‘balance’, and ‘conservation’ (MOE, 2011).

Learning as Progression

All of these standards structure curricula in accord with the cognitive development of the students. For instance, the American NGSS is arranged around the notion of learning as a developmental progression (NGSS, 2013, Appendix E). Hence students can continually build on and revise ideas, initially starting from those they have obtained in everyday life and proceeding to the construction of a scientifically coherent knowledge base that integrates ideas from natural sciences and engineering. Hence, students begin studying science in elementary school with an emphasis on making observations of the natural world, and they are taught basic concepts from life sciences, physical sciences and earth and space sciences (TIMSS & PIRLS, 2015d).

As we shall see below, in general, all of the standards follow a similar approach where the primary science curriculum is highly integrated and involves phenomena close to students' everyday lives. Disciplinary boundaries are then introduced in the lower or upper secondary level. Many of these standards are also structured around several selected core ideas that form the basis of the primary and lower secondary curriculum. For instance, In Japan, it is explained in the Course of Study how the contents within basic physics, basic chemistry and basic biology in the upper secondary level relate to the four thematic pillars (energy, particles, life, and earth) that form the foci for the science curriculum for primary and lower secondary levels (MEXT, 2017b, 2017c, 2017d). In the Israeli standard, the learning progression is described as a spiral (cf., Bruner, 1960) where students advance through each level in increasing sophistication, with new material added in from various contexts and perspectives at each grade level (Ministry of Education, 2016).

In the high school curriculum of China, there are also explicit pedagogical suggestions on how to structure lessons based on central disciplinary ideas (MOE, 2017a). For instance, the principle that a substance's structure determines its properties, and that the properties of a substance reflect its structure, is a central idea in chemistry. This idea can be taught, and then consolidated and developed, through several stages. During the learning of periodic trends in the compulsory chemistry courses, students can learn how the position of an element in the periodic table relates to the structure and the properties of a substance formed by this element. Then, in electives where students are taught about chemical bonds and matter, they can learn how the features of chemical bonds can be used to predict and explain the properties of a substance. Finally, in the elective of 'organic chemistry foundation', they can explore how functional groups also allow predictions of the properties of a substance.

OVERVIEW OF CURRICULUM CONTENT WITHIN SOME NATIONAL SYSTEMS

Brazil

The Ministry of Education of Brazil established the BNCC for primary and lower secondary education (MEC, 2017). For the primary syllabus, there is a focus on phenomena in the students' immediate experience. The Brazilian primary science syllabus is divided into three themes: 'matter and energy', 'life and evolution', and 'earth and universe'. In addition, contexts from historical, social, cultural, environmental, health and technological aspects are also included in each theme (MEC, 2017).

The standard suggests a continuation of these thematic units in the lower secondary schools (MEC, 2017). For instance, the exploration of energy can be extended to a wider scope concerning its production systems and impacts on the environment (MEC, 2017). A new theme, 'the life, earth and cosmos', results from the aggregation of two thematic units ('life and evolution' and 'earth and universe') developed in elementary school. This relates learning in biology (e.g., the origin and evolution of life and the metabolism of living things), astronomy (e.g., the planet, stars and cosmos), physics (e.g., applications of nuclear reactions) and chemistry (e.g., the greenhouse effect and climate change).

Within the science curriculum guide for upper secondary level published by the Brazilian State of Sao Paulo, there are many examples of connecting the learning of natural science with the human sciences (SEDUC-SP, 2011). For instance, it describes how historical periods are guided by technical and scientific knowledge applied in economic activities; and how, often, commercial trade, international disputes and territorial domains are dependent on the development of productive forces closely associated with scientific knowledge (SEDUC-SP, 2011). Also reflected, is how some fields of scientific research (e.g., cosmology and evolution), are informed by philosophical scholarship. The science curriculum here is divided into traditional disciplines of physics, chemistry and biology (SEDUC-SP, 2011).

China

The Chinese standard suggests primary science is to be constructed based on four key areas - ‘materials science’, ‘life science’, ‘earth and universe science’ and ‘technology and engineering’ - through focusing on objects or natural phenomena in students’ everyday lives (MOE, 2017b). Across these four content areas, there is an overarching theme of ‘science, technology, society and the environment’ which highlights that these four areas are interrelated and reinforces the integrity of the natural world (MOE, 2017b).

In addition, for the primary curriculum, a concept map was created for each content area to note relationships between the concepts (MOE, 2017b). For ‘life science’, the concept map (MOE, 2017b, pg, 34) is redrawn (translated) as Figure 1.

The lower secondary curriculum builds on the same four key areas (MOE, 2011). However, the sub-themes are different. In contrast to the integrated curriculum in the primary and the lower secondary level, the high (i.e., upper secondary) school science curriculum is divided into the discrete disciplines of physics, chemistry and biology (MOE, 2017a; Yang, 2009). For each discipline there are compulsory courses that teach the foundations of the discipline, as well as a range of electives to meet the interests and needs of different students (MOE, 2017a): although some of these are actually required pre-requisites for progression onto related university courses.

For instance, for the chemistry curriculum, the compulsory elements are: ‘chemistry and experiential inquiry’, ‘common inorganic materials and their applications’, ‘foundations of the structure of materials and principles of chemical reactions’, ‘simple organic materials and their applications’, and ‘chemistry and societial development’. The electives which must be chosen for progression to university, and which are set-up based on major chemical research areas are: ‘principles of chemical reactions’, ‘material structures and properties’ and ‘organic chemistry foundations’. Other available electives are: ‘experiential chemistry’, ‘chemistry and society’ and ‘chemistry in development’. These integrate chemical knowledge with societal development and contemporary issues, as well as promote chemical literacy and aim to stimulate interest and curiosity. Throughout the national standard, there are also many suggestions for ways of relating content between disciplines. For instance, in teaching about organic molecules, teachers are given pedagogical suggestions for how to link the chemistry to life and material sciences.

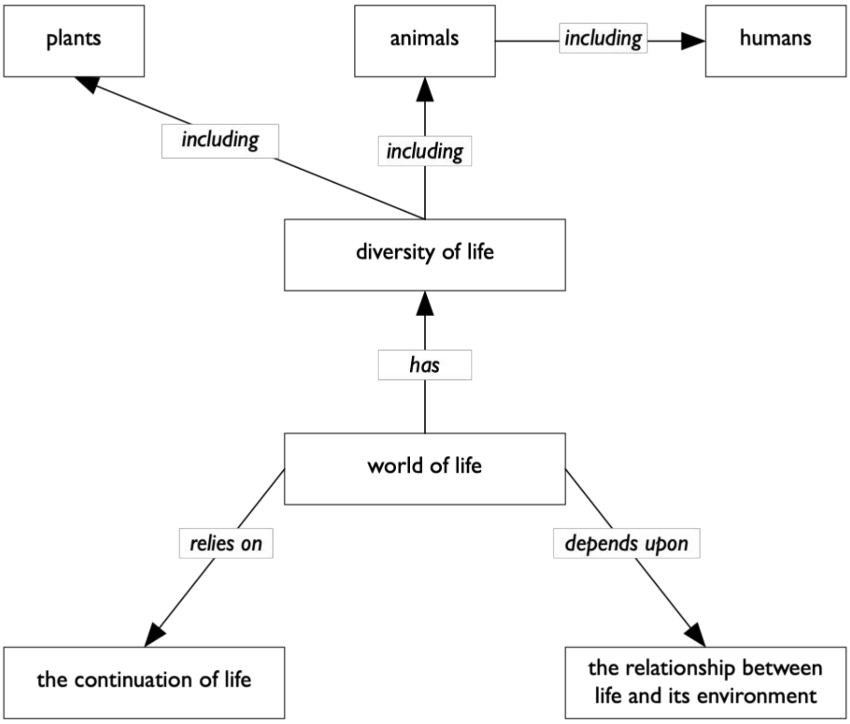

Figure 1. Concept map showing the core themes of the Chinese school science area: life science.

Germany

In Germany, at primary level, integrated science (Sachunterricht, which is an integrated subject of natural *and social* sciences) is a compulsory subject in all 16 states, but there is no national federal standard (TIMSS & PIRLS, 2015a). The curriculum guide for the primary level set by one state, North Rhine-Westphalia, suggests teachers should plan lessons for Sachunterricht that bundle together the scientific, technical, nature-related, social and cultural, historical and economic aspects in areas such as (QUA-LiS NRW, 2008):

- nature and life
- technology and the world of work
- space, environment and mobility
- people and community
- time and culture

There is an emphasis on interacting with nature (as in Japan, see below), as well as having environmental and health education for primary students in order to develop a sense of responsibility and positive attitude to nature, life and society. Importance is also placed in teaching the geographical features in local and more distant areas; ethics and culture, and skills development; as well as science concepts, in topics such as (QUA- LiS NRW, 2008):

- substances and their transformation
- heat, light, fire, water, air, sound
- magnetism and electricity,
- body, senses, nutrition and health
- animals, plants, habitats

After successful completion of primary school, students are assigned to different secondary school tracks depending on their abilities - based on prior achievement and predicted academic aptitude (EC, 2019a, 2019b). The three different educational tracks (Hauptschulbildungsgang, Realschulbildungsgang, Gymnasialer Bildungsgang) qualify students for different destinations such as vocational training or tertiary education. They have different lengths of completion and teach different content, with variations in depth of treatment and coverage within topics. For most states at the secondary level, science is taught as separate disciplines: biology, chemistry, physics and geography (TIMSS & PIRLS, 2015a). Yet some states offer science as an integrated subject in certain secondary school tracks, covering some or all of the disciplines (mostly at Hauptschulen or Gesamtschulen).

The German national standard for secondary level supports systematic knowledge-building from several fundamental concepts. In physics, four basic concepts are identified which are 'systems', 'matter', 'energy' and 'interaction' (KMK, 2004c). For Biology, the basic concepts are 'systems', 'structure and function' and 'development' while those for chemistry are 'chemical reactions' (KMK, 2004b), 'structure-property relationships', 'substance-particle relationships' and 'energetics' (KMK, 2004a). The standards documentation also describes how these concepts relate to each other across disciplines.

Israel

In Israel, in general, the curriculum content is divided into three main areas: material science, which relates mainly physics and chemistry topics, as well as life sciences, and technology (Ministry of Education, 2016). These areas include sub-topics that concern environmental issues and the applications of science in everyday life and within the society. This results in six main domain areas for primary level: 'matter', 'energy', 'the man-made world', 'systems and processes in living organisms', 'ecosystems', and 'the earth and the universe' (which includes astronomy). The lower secondary level consists of similar domains as the primary levels (TIMSS & PIRLS, 2015b). However, the topic of 'the earth and the universe' is then located under the geography curriculum and replaced by 'cell structure and function' (TIMSS & PIRLS, 2015b).

In Israel, science remains a compulsory subject only until lower secondary level, but attempts have been made to encourage students to choose to continue studying science (TIMSS & PIRLS, 2015b). In the upper secondary level, students can choose between two different 'tracks': the general track or the technology track (Nuffic, 2017). Regardless of the selected track, students must complete the general components (where science is *not* compulsory) set by the Ministry of Education. As in China (see above) and the US (see below), upper secondary students enjoy a wide range of electives depending on their interest and aspirations including academic subjects such as geography, physics, biology, computer science, as well as technical and more integrated subjects such as electrical / mechanical / civil engineering, and microbiology (Nuffic, 2017).

Japan

In Japan, science instruction begins in the third grade as a compulsory subject. The primary science curriculum involves learning from two content areas, 'matter and energy', as well as 'life and earth' (MEXT, 2017d). Here a heavy emphasis is put on encouraging children to develop a loving and protective attitude towards nature and cultivating thinking skills. The subject living environmental studies which coalesces social studies and science was also established as early as 1977 (Nakayasu, 2016). It was argued that it would be effective for 1st and 2nd grade students to understand both social and natural phenomena through experiential learning activities. Similarly, in the 1998-1999 revision of the Course of Study, the lesson period for integrated studies was also established, which aims to enable students to apply materials they have learnt and to think independently about life through cross-disciplinary and enquiry studies (Nakayasu, 2016). Each school is given the freedom to develop and conduct the period for integrated studies as considered best suited for its students and may include themes such as information or environmental education (Nakayasu, 2016). This remains a compulsory subject for all levels from primary to upper secondary level.

For lower secondary level, the science curriculum is divided into two fields: physical sciences, and biology and earth sciences (MEXT, 2017b). Physical education is combined with interdisciplinary health education as a subject while home economics is integrated with technology education since both concern everyday life and are thus considered best taught through experiential learning (MEXT, 2017a). The latter combines learning in fields such as material science, biotechnology, the technology of energy conversion, and information technology.

For the upper secondary level, students can choose from studying (a) ‘science and our daily life’ and two options from ‘basic physics’, ‘basic chemistry’, ‘basic biology’ and ‘basic earth science’, or (b) three among ‘basic physics’, ‘basic chemistry’, ‘basic biology’ and ‘basic earth science’ (MEXT, 2017c). While the latter option may seem to imply less integration among the disciplines, each subject includes topics linking with everyday life and the latest technological developments to form overarching themes. The most recent revision also introduces a new area ‘enquiry-based study of science and mathematics’ in the upper secondary level that aims to combine ‘mathematical thinking’ and ‘scientific thinking’ into science learning (MEXT, 2017c). Students who choose to do this enquiry-based option are motivated to think in various ways and draw together knowledge and skills from several disciplines.

Russia

Like the German curriculum, at the primary level (grade 1-4) in Russia, science learning is founded in an integrated programme of social and natural science studies under the course ‘surrounding world’ (which has approximately 70% natural science content) (TIMSS & PIRLS, 2015c). The Federal State Education Standards for Primary Education aim to expand, organise and deepen students’ ideas about natural and social phenomena and are intended to equip students with a perspective for viewing these two areas as components of a unified world (Ministry of Education of the Russian Federation, 2015). For the science side, students study biology-related topics (e.g., ‘nature’, ‘plants’, ‘animals’, ‘the unity of living and non-living nature’ and ‘the human body’), geography-related topics (e.g., ‘earth’s structure’), astronomy (e.g., ‘stars and planets’) and chemistry related topics (e.g., ‘solids, liquids and gases’) (Ministry of Education of the Russian Federation, 2015).

In grades 5 through 9, students learn through an integrated course nature study in grade 5, followed by separated science disciplines: biology (Grade 6-9), geography (grades 6-9), physics (Grades 7-9) and chemistry (grades 8-9) (TIMSS & PIRLS, 2015c). There is no strong emphasis on cross-disciplinary learning (e.g., for physics, students are required to learn about mechanical phenomena, heat phenomena, electromagnetic phenomena and quantum phenomena), but there are components related to everyday contexts and themes such as technology and environmental protection (Ministry of Education of the Russian Federation, 2017; TIMSS & PIRLS, 2015c).

United States

In the United States, students begin studying science in elementary school with an observational emphasis and cover basic concepts from life sciences, physical sciences and earth and space sciences (TIMSS & PIRLS, 2015d). In most states, content in these topics will continue to be taught in the middle school, but in greater sophistication, and the specific content area taught may differ across the grades (TIMSS & PIRLS, 2015d).

For instance, for California, it is suggested that grade 6 focuses on earth and space sciences, grade 7 on life sciences, grade 8 on physical sciences, while engineering, technology and application of science is taught throughout grades 6-8 (CDE, 2019). However, to graduate from high school, students must study science, including biological and physical sciences, for two years, and there are options to study more science subjects from electives such as geology, astronomy and environmental sciences (CDE, 2020).

CHALLENGES OF CURRICULUM DESIGN: THE CASE OF THE ENGLISH NATIONAL CURRICULUM FOR SCIENCE

This brief survey from selective national contexts presents curriculum as represented in official documentation, which may not always reflect the interpretations and priorities of teachers or the perceptions of the learners experiencing the curriculum as enacted. To illustrate this, we consider some of the issues that have arisen in relation to curriculum policy and implementation in one national context.

England has a national curriculum that offers some insight into the complexities regarding how curriculum policy impacts upon, and may be subverted by, custom and practice. A detailed account of the development of the English National Curriculum for Science (ENCS) in its wider educational context (e.g., policies relating to assessment and teacher 'training' and official guidance on pedagogy) would necessarily be quite nuanced, and we necessarily limit ourselves to some brief comments. These, whilst not comprehensive, offer some sense of the challenges that faces curriculum developers and policy makers in devising curriculum to meet diverse educational and societal needs (as discussed earlier in this chapter) and against a background of implicit, taken-for-granted, assumptions.

England has a strong and proud tradition of science education, and indeed was influenced at the end of the nineteenth century by ideas that became widely discussed globally only much later - such as enquiry learning (Jenkins, 1979). It had a long tradition of active teacher associations, curriculum development (in particular, teacher-led development) and curriculum reform work, such as the Nuffield curriculum projects (Nuffield Currculum Centre, 2006), as well as teacher involvement in the development of diverse examination specifications (Misselbrook, 1972b).

Establishing 'Science' as a Unitary Curriculum Subject

Much of this changed with the implementation of a national curriculum (Statutory Instrument, 1989) at the start of the 1990s, when for the first time the government decided to tell science teachers what to teach, to whom, and, later, even suggested how. Science became a compulsory school subject for the first time, for all students aged from 5 to 16 years - and biology, chemistry and physics officially ceased to be school subjects in the compulsory school years. (This continued to be so for a period of over two decades.) Previously, the only school subject that had been legally required was religious education, although in custom and practice secondary students studied science to age 14, and many schools expected most students to then continue with at least one science option.

The ENCS's 'programme of study' was organised into four sections, or 'attainment targets', Sc1-4, one of which (Sc1) related to the generic area of scientific investigations. The other three (Sc2-4) were in effect, although not explicitly labelled as, biology, chemistry and physics (DfEE/QCA, 1999). The curriculum was intended to offer a broad and balanced science education (Jenkins, 1998), but, officially at least, biology, chemistry and physics ceased to be formal school curriculum subjects (Taber, 2005b). It should be acknowledged that in part this approach was motivated by the phenomena of gender imbalance in uptake of the science subjects at age 14 and, in particular, that of most girls electing not to study any physics (Kelly, 1981; Taber, 1991).

The curriculum was subject to a range of tweaks over a period of some years. It was recognised that, as enacted, the intended inclusion of a perspective on the nature of science (in particular a focus on ideas and evidence) was not being widely fulfilled, and Sc1 was strengthened both by modification of the programme of study (expanded to scientific enquiry rather than just scientific investigations), and by changes to the associated the official assessment regime (QCA, 2002).

Rejecting a Reformed Curriculum for Science

The most significant revision of the ENCS involved a major reworking of the curriculum structure and content in response to scholarship that argued that a traditional, content-heavy curriculum did not meet the need to develop scientific literacy for all learners (Millar & Osborne, 1998). A revised secondary level ENCS (QCA, 2007b, 2007c) offered a greater balance between specific scientific content and more generic aspects of a scientific education such as transferrable skills (thinking skills, communication skills) and an understanding of the nature of science and its place in society (QCA, 2005, 2007a). Despite bold claims about how this new curriculum would raise standards, it was subject to a good deal of public criticism - much along the lines that less prescribed content and more focus on societal issues meant a less rigorous education (which from an educational perspective appears as considering that extensive rote learning should be valued over understanding concepts and engagement in thinking through complex and nuanced issues).

A more conservative curriculum was re-instated, one that sought to "develop scientific knowledge and conceptual understanding through the specific disciplines of biology, chemistry and physics" (DFE, 2015). Whilst the broader aims that had influenced the earlier revision had certainly not been rejected, it seemed that there were widespread implicit (taken-for-granted) beliefs that a high-quality science curriculum needs to be organised in terms of formal disciplinary knowledge, and that the quality of a scientific education is proportional to the amount of science content squeezed into it. Thus, although the broad aspirations of the ENCS are certainly akin to those inherent in other national standards discussed earlier, in this national context any progressive elements that might be intended to support such aspirations were treated with distrust.

Any curriculum context is likely to be complex. This is certainly the case in England. As one example, although something like 93% of students attend state-funded schools, those schools are designated in a wide range of (sometimes overlapping) ways as a result of successive policies of various governments (community schools, subject-specialist schools, academies, free schools, comprehensive schools, voluntary-aided schools, voluntarycontrolled schools, university technical colleges…) and an increasing proportion of state schools (currently over a third) are not actually required to follow the statutory National Curriculum! Despite this, the recognised system of national examinations, which are taken by most students in most schools, are regulated, and are required to follow specifications closely based on the ENCS.

Indeed, the respect for the official representation of science in the ENCS is such that it has been shown that where the curriculum specification has been poorly drafted so as to suggest teachers should teach scientifically dubious principles, the questionable wording is nonetheless directly copied from the curriculum documents, through guidance for examination boards, to examination specifications, and even on to guidance for students and parents published on school websites (Taber, 2019a). This might be expected in a society with a special reverence for authority, but in the case of England it seems more to be cult of identifying educational standards with 'teaching to the test': that is, valuing a clear statement of what is to be learnt (regardless of its educational or scientific merits) that can act as target knowledge and which teachers then know will be the basis for evaluating their students and their own professional effectiveness.

Science and the Disciplines

With the introduction of the original version of the ENCS the status of biology, chemistry and physics as school subjects became fuzzy. As the school subject was science, the standard school examination was in science, which - for the majority of students - was treated as a double subject (that is, leading to two grades when counting the number of school examination passes) taught to students aged 14-16 years. There was a facility for a single award (i.e., with the same weighting as other subjects such as mathematics or geography, based on reduced subject content) which was primarily intended for low achievers and to allow some students to study several languages and spend less curriculum time on science. There was also a facility for a triple science award, which did offer separate grades for biology, chemistry and physics, based on an examination syllabus that augmented the ENCS with extra topics from each discipline. Yet schools were not required to offer this - so whilst some schools did, many did not.

It is common for there to be unintended consequences of any government policy, and this is certainly what is found with curriculum policy. The matter of whether the separate science disciplines were timetabled as formal school subjects (given the prescribed curriculum) could seem to be an administrative matter, or simply a choice about presentation, but in practice it had substantive effects (Taber, 2006).

Where schools did not have to offer the triple science option, many did not. Independent schools catering for those who prefer to pay for their children to be taught outside the state system, that is, by definition, people with the means to afford private education, were generally likely to maintain discrete departments of biology, chemistry and physics and to offer the triple science option. This is not just a matter of the labelling of school subjects and examinations, as those taking triple science were being taught more science, and so were inevitably (on average) better prepared to commence advanced science courses in post-compulsory education when compared with students only able to take ‘double award’ science.

State schools that included sixth-forms (for students aged 16-19 years) where biology, chemistry and physics were taught as separate elective subjects were also likely to retain discrete departments and offer the triple science option to (all or some of) their students aged 14-16. Often in urban contexts, however, the state schools only take students to age 16, at which point the young people apply for courses in post-compulsory colleges. Many 11-16 schools, especially those in areas of serving people of modest socio-economic status, judged that they did not have the resources to offer the optional triple science course, and so denied this as an elective to their students. (Some schools offered the option to their highest achieving students, but without increasing the amount of teaching – so increasing the breadth of content, but diluting the depth of study.)

This was eventually recognised as an equity issue, a form of discrimination against those students living in areas of relative deprivation, and the then Prime Minister decreed that all state schools would have to provide the option of studying triple science to students who performed well on national science tests at age 14 (Blair, 2007). Even then, in some schools, alternative triple science combinations were considered to meet this expectation - as the school subject was just science, it was possible to consider triple science as biology, chemistry and psychology, for example.

Implications of Curriculum Policy for Teacher Recruitment and Development

This response makes sense when considering the effect of the ENCS on teacher preparation and recruitment. Schools with discrete biology, chemistry and physics departments clearly needed to seek to maintain staffing across these areas. Those schools that adopted a unitary science department, and looked to recruit science teachers *per se*, did not necessarily manage to maintain a balance across science specialisms - even if this was felt desirable, it was not considered strictly necessary given the school subject was ‘science’. This mattered because, although there was not a severe shortage of qualified science teachers looking for posts, schools often found the field applying for a ‘science’ teaching position consisted predominantly of biology specialists.

In part, this related to the teacher ‘training’ regime - as when the ENCS made science the school subject, departments of teacher education did not need to look to recruit a balance between the different science specialists, as their task was to attract good *science* graduates and prepare them for *science* teaching. Some university education departments maintained a strong distinction between disciplines in their recruitment and formed specialist subgroups within science teaching courses, and so - at least - set out to maintain a balance between biology, chemistry and physics. Yet, given that many more life scientists were seeking entry to ‘training’ courses, it was largely the more elite institutions (where the number of applications from qualified applicants well exceeded places available on courses) that could hold to such a policy. So, for much of the early period of the ENCS, the system was preparing cohorts of science teachers that were strongly biased towards biology, and against physics.

This imbalance was not just a matter of a glut of biology graduates, or a higher demand for physical science graduates to enter other employment areas such as finance, but also the way that the ENCS made preparing for teaching less attractive to many physicists and engineers. Pre-ENCS, someone completing a degree in physics or mechanical engineering (for example) who wished to teach would likely consider they were best suited to just teach physics, or to teach physics and mathematics. For that matter, a chemistry graduate might choose to prepare to teach chemistry and physics (as the senior author did), or a life sciences graduate might choose to teach biology and chemistry. Yet, when the ENCS was imposed, this was no longer possible - an applicant had to prepare for teaching a school curriculum subject - such as mathematics *or* 'science' - and if they took the latter option they then had to (at least during the training year) teach across the science curriculum (TTA, 1998).

Schools were allowed to recruit someone who had completed initial teacher education in science (but with no specific preparation for mathematics teaching) to teach physics with some mathematics, or someone who had completed initial teacher education in mathematics (but with no specific preparation for physics teaching) to teach some physics as well as mathematics - but the general expectation was that new teachers would teach in the curriculum subject for which they had 'trained'. The official adoption of science as a school subject, and the associated decision to avoid labelling of biology, chemistry and physics material within the ENCS documentation, was therefore not just a matter of presentation, but something that had real effects on school staffing, teacher preparation, and so (in many schools) student opportunities to be taught science topics by disciplinary specialists.

Systemic Inertia Resisting Reforms

Whilst this did serious damage to science education in England over a period of over two decades, it should also be pointed out that many science teachers in post at the time the ENCS was introduced saw themselves as primarily biology teachers, chemistry teachers, or physics teachers, and that tradition remains to this day in many, but not all, schools. So, even when all the official apparatus of curriculum, assessment, teacher preparation and professional development presented science as *the* school subject to be taught by science teachers, many in the profession continued to take for granted that actually science consisted of discrete disciplines that, at least for the older children, were best taught by subject (i.e., science discipline) specialists. So, the case of the ENCS both reflects how policies can have unintended, damaging effects, and also how the conservative tendency to assume the status quo, can to some extent resist policy changes through continuing traditions of practice that are only changed superficially by apparently radical shifts. That is, the conservative nature of traditions can not only resist progressive change, but also, to some extent, mitigate the potential damage of ill-advised reforms.

Before leaving the issue of the representation of the disciplines in the science curriculum it is worth noting that the division of the ENCS into sections that were based on (if not labelled as) the disciplines of biology, chemistry and physics led to issues about how to include material that did not readily fit these areas. Material about earth and space sciences moved into, and out of, the curriculum. Material from earth sciences, best identified with geology, was pushed into Sc3, in effect the chemistry section (Wilson, 2012), although it was not well received by many science teachers. Teaching these topics was not part of most science teachers' preparation - and this material was treated as unfamiliar chemistry by many of those considering themselves primarily as biology or physics specialists, whilst also being considered to not actually be authentic chemistry by many chemistry specialists.

Interpreting Curriculum Documents

Curriculum documents themselves are simply representations of ideas and intentions (of policy-makers, of curriculum developers), and before they can influence practice they need to be interpreted by teachers and others who mediate between the document and classroom implementation. When the ENCS was revised and the content-heavy programme of study was replaced by a much more lightly-specified outline of a more limited range of topics to be covered (QCA, 2007b, 2007c) this was intended to give teachers more flexibility, and should have allowed a reduction in the weight of content to be 'covered': yet many teachers considered that they were still expected to teach what had been previously specified, even when it did not actually appear in the new curriculum. This revision offered a chance for greater emphasis on the nature and processes of science, yet in practice most teachers continued to focus on subject matter content (and a lot of it) expecting the assessment regime to be largely unchanged.

Not surprisingly then, although the curriculum documentation might reflect quite sophisticated understanding of aspects of the nature of science, this was seldom further reflected in student learning (Taber, Billingsley, Riga, & Newdick, 2015). Indeed, although, in common with global trends, curriculum documents might explicitly ask for an emphasis on enquiry within science, the formal subject-based structure of the curriculum (arranged around traditional clumps of disciplinary knowledge, not scientific practices) implicitly gave another message (Taber, 2018b).

Some other national standards suggest key concepts that can provide a core anchoring point for developing student understanding in science (see 'Overview of curriculum content within national systems' above). This provides an opportunity to suggest to teachers where the key emphasis of science teaching should be, by selecting process-based (e.g., theory change) or interdisciplinary (e.g., feedback in natural systems) themes. In the ENCS, it was suggested that the five key scientific ideas around which teaching could be planned were cells, interdependence, particles, forces, and energy (Key Stage 3 National Strategy, 2002a) - which largely aligned with disciplinary subject matter (even if energy and interdependence certainly offered potential for much interdisciplinary work).

The short-lived 'content-lite' version of the curriculum potentially offered an opportunity to engage with topics in detail, and so to seek to ensure secure conceptual understanding of key concepts. Again, teachers were certainly officially encouraged to teach for understanding, and indeed constructivist pedagogy was recommended (Key Stage 3 National Strategy, 2002b). Yet teachers were prepared for adopting constructivist pedagogy by a training regime based on sets of centrally prepared professional development sessions, presented to groups of teachers by consultants following a published script. If ever there was an example of "do not do as I do, do as I tell you" (or exemplification of the cruel jibe, that "those who can, do, and those who can't, teach; and those who can't teach, train teachers") this officially sanctioned modelling of poor teaching practice carried a strong implicit message (Taber, 2010).

CONCLUSION

In this chapter we have considered the question of organising a curriculum through timetabled subjects, with particular focus on the example of science / the sciences. We set out considerations for curriculum in terms of the different perspectives on the purposes of education (and so of curriculum as a means to respond to such purposes). The different options we discuss are not necessarily conflicting - one can seek to do many things in a curriculum - but the balance of imperatives and priorities adopted will have implications for the content, organisation and presentation of the curriculum. We offered a brief survey of how science curriculum is organised and presented across a number of major nations. We also discussed in a little more detail the case of the ENCS as an example of how curriculum can be a challenging matter for those charged with its design and implementation.

Our brief survey only highlights some of the 'headline' points from a small range of national educational systems (and even there, the extent to which curriculum is prescribed at a national, rather than more local, level varies). However, it seems that even within this modest overview there is much variation in how science is presented within the curriculum.

One fairly common theme is building progression into the science curriculum in the sense that, in general, curriculum is often more integrated in the early years, and the traditional disciplines of biology, chemistry and physics are more likely to be explicit school subjects for older students (in some cases, even taught in different grade levels). There are, however, different models in terms of whether curriculum is differentiated for different groups within an age cohort, and when, and how much, choice is given to students in the science(s) they study. Offering some level of choice (whether in curriculum subject, topics, or simply examples and case studies within a topic) is not only a means to support the development of personal autonomy and responsibility, but something that can engage and motivate science learners (Taber, 2007).

Different decisions have also been made in terms of how and when to show the links between science and other curriculum areas, and in terms of how the applications of science, the social context of science, and the treatment of socio-scientific issues are presented. In some national systems the traditional disciplinary identities are still represented as school subjects, but with a range of ways of embedding science content in broader contexts, and of integrating content across and beyond the sciences, either at the level of the school subject, or in terms of key themes or core ideas around which the content within subjects is organised.

Even limiting our focus to the example of science / the sciences demonstrates the wide range of choices that can be made. There is not a clear boundary around what science is. So, we see science being conflated with technology in some contexts, where it would be seen as a related but quite different set of practices elsewhere. A parallel point could be made about science and mathematics. Mathematical ideas and tools are applied in science - but mathematics as a discipline is quite distinct. Geography and psychology may at times be seen as part of science - although more generally they are seen as quite separate: geography is often seen as a humanities subject and psychology as such may not be recognised as belonging in the compulsory school curriculum. Both splitters and lumpers are faced with options concerning *how* to break up, or fit together, curriculum elements.

There is something of a tension between what may be considered a more student-centred approach (perhaps favouring topics and themes based on applications met in everyday life, or deriving from broad issues of wide concern such as health, the environment, and sustainable development) and what could be considered a more academic approach based around disciplinary structure - certainly in the case of the ENCS much public and political opinion (even if likely due to the efforts of a relatively small but vocal range of people with strong concerns) reflected an assumption that issues-based science teaching was less rigorous than teaching based around traditional science topics deriving from disciplinary sub-fields. When so much cutting-edge scientific research is based on work which is described variously as cross-disciplinary, trans-disciplinary or inter-disciplinary, this may seem to suggest a popular image of science which is itself out of date.

Yet it is also the case that in national contexts where most undergraduate training produces graduates in chemistry or electrical engineering or astrophysics or biochemistry - and so forth - disciplinary structure may actually both map onto much of what university departments are looking for in applicants to such courses, and also reflect where potential recruits to teaching, graduating with such degrees, have strengths. Certainly, expecting teachers to model the disciplinary practices across STEM subjects, or even across just biology, chemistry and physics, may be unrealistic when most new graduates only have a modest experience of practice within one major disciplinary tradition.

This makes strong conclusions or recommendations difficult. Our main take-away points are that:

- there are a range of educational aims that offer different priorities for planning and organising curriculum, which might suggest that a ‘mixed economy’ of integrated and specialist learning experiences is most useful, especially when customised for different groups of students (Taber, 2018); but there is also a range of constraints in terms of what can reasonably be expected of teachers and the complexity of timetabling in schools;
- however, it is common to look to modify the nature of the curriculum experience as students develop and progress: such that formal disciplinary structures can become more apparent in senior

years, building upon more integrated and contextualised learning of science in the early years;

- there should be a balance in science curriculum learning objectives between specific science content, and wider aspects of science learning (process skills, etc.), but that this will likely fail (as seen in England) unless it is explicitly reflected in curriculum organisation and, in particular, high-stakes assessment.

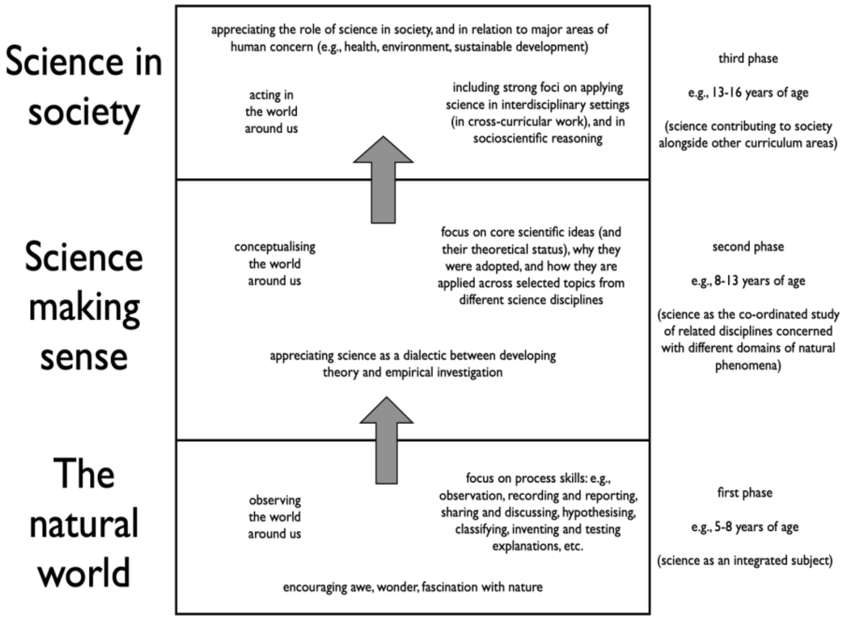

Figure 2. One possible outline for thinking about science in the school curriculum.

Perhaps science education should best move from enquiry-directed nature study based upon close and extended observation, question-posing and other process skills (Taber, 2019b); through a more formal science curriculum experience based around disciplinary structure, that introduces the key concepts from the science disciplines (but offering deep engagement with some carefully selected science topics, rather than a comprehensive survey); to a science education that engages with socio-scientific issues, and encompasses cross-disciplinary work with other curricular areas (see Figure 2).

As a final point, we would suggest that given the wide diversity in how science curriculum is structured, described, and organised internationally, there is scope for a research programme looking at how these different alternatives are understood by teachers, implemented in classrooms, and experienced by students. Ultimately, we want students to understand, appreciate, value, and wish to engage with, science, and so perhaps what is most important is not how we may choose to split or clump curriculum elements but rather the degrees of coherence, relevance and engagement perceived by the learners.

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