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Knowledge sans frontières?: Conceptualising STEM in the curriculum to facilitate creativity and knowledge integration

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Introduction

The present chapter explores two related themes of particular importance in considering intelligence and the nature of giftedness - creativity and knowledge integration - in the context of teaching and learning STEM subjects. The chapter draws upon ideas about the natures of disciplines, curriculum, and cognition, to consider the potential role of STEM education *qua* STEM education (what is labelled here ontological−STEM, 'o−STEM', education) in supporting the development of gifted learners. It is argued that there are options in how STEM is understood as a curriculum area, and the choices made have consequences for how learning is experienced by students. A curriculum model incorporating o−STEM provision has the the potential to offer learning activities of more obvious relevance to the professional practice of science and technology (something which may increase motivation for many learners). Of particular relevance to developing gifted traits and challenging gifted students, o−STEM education offers greater opportunities for making creative links, and forming more integrated conceptual frameworks. The core thesis, then, is that STEM education has a particular potential for supporting and developing gifted learners providing that the STEM curriculum is organised so that 'STEM' is more than an umbrella term for a set of distinct academic subjects.

Developing gifted learners - but who are the gifted?

The notion of giftedness adopted in this chapter is a pragmatic one which has been argued in more depth elsewhere (Taber, 2015b, 2016b) based on the idea that all students (and especially young people who are legally required to attend school) are entitled to provision that is genuinely educative in the sense of supporting them to significantly develop their knowledge, understanding and skills. That, in turn, rests on a balance between (i) learning activities that offer sufficient challenge to provide the basis for substantive new learning, and (ii) sufficient support from the teacher to enable genuine progress.

That is a simple (and one might hope) obvious *principle*, but it is not easy to ensure *in practice* because

> a) an individual student will often have a very uneven profile of existing knowledge, understanding and skills that makes it difficult for teachers to plan lessons in advance informed by knowledge of how much challenge and support a particular student will benefit from in any particular lesson;
>
> b) teachers generally have class sizes of greater than one (usually considerably so) - and in any such class each student brings their own unique profile of strengths and limitations, and so particular individual needs in terms of being supported and/or challenged by particular curriculum elements.

The first point, (a), suggests that effective lessons can only be planned in advance to a limited extent, as - realistically - teachers can only ever have a partial mental model of the current capacities and strengths of the different individual learners in their classes (Taber, 2001). Consequently, effective teaching requires 'on-line', real time, interactive work of informal (formative) assessment informing consequent adjustments to teaching presentations (Taber, 2014). That certainly does not imply lessons should not be planned in advance, but rather than what is planned must encompass considerable flexibility.

The second point, (b), suggests that what is an effective lesson for one student will likely be suboptimal for at least some class mates - unless the lesson is taught in a way that it can be customised to some extent for different students. Of course, in practice, a school teacher may have twenty or more hours of classes each week with perhaps thirty different students in most of those classes (so that there is a sense in which such a teacher has to prepare something like five hundred lessons per week if each student/lesson combination is seen as somewhat unique).

Teachers can and often do develop high levels of skill in responding to this conundrum, but it is worth noting that we expect a great deal of teachers in dealing with this challenge.

In reality, in some classrooms there is a tendency to pitch lessons at either the 'lowest common denominator' (what every student can manage) or some kind of 'average' (so most of the students can cope). Aiming (*i.e.*, deliberately) for the lowest common denominator is lazy teaching, and is likely to lead to many students being bored - and in many contexts to some students becoming disruptive. Students should respect their teachers and the rights of their classmates to study - but teachers who waste students' time by giving them routine activities with limited learning potential do not offer good role models for how to respect others. Aiming teaching at the middle ground is probably more common, and indeed for a novice teacher still developing their skills this may even be what is recommended by more experienced colleagues as a way of coping with the demands of class teaching. If one is just learning to differentiate lessons effectively, then working out from the middle seems intuitively the best starting point - even though there is an alternative argument that teachers might best aspire to offer effective differentiation that *starts from what the most able find challenging but can manage* and then builds in support for the other learners (Rubie-Davies, 2007; Taber, 2015a; Taber & Riga, 2016).

Where there is a 'reversion to the median' mentality (i.e. in effect teaching to the average attaining students) in classrooms there will be one group of students for whom the set work is too challenging without extra support; and another group of students able to complete the work without difficulty, but also without needing to fully engage (Tomlinson et al., 2003). For these latter students, the work is routine, and does not push them beyond what they are already well capable of. They may produce 'good' work in terms of the requirements set for them, but they learn little. When teachers cannot cope with differentiated teaching they seldom pitch work at the most able students (and here 'able' is simply meant in the context of that day's lesson) as this will lead to most of the class making frequent demands for help and will likely reduce motivation and engagement, in turn leading to distracted students and off-task behaviour among much of the class.

There are many ways to define and identify gifted students, but here the term is used for those students who will not be sufficiently challenged by teaching when the curriculum is presented in an insufficiently differentiated manner - those "who, given appropriate support, are able to either: achieve exceptionally high levels of attainment in all or some aspects of the normal curriculum demands in school science…; or undertake some science-related tasks at a level of demand well above that required at that curricular stage" (Taber, 2007, p. 7). The term 'developing' gifted learners is intentionally ambiguous here. Effective education can help the development of those students identified as gifted - but we should also aspire to develop more students towards being considered gifted. Teachers should aim not only to respond to obvious ability but also to uncover latent potential.

What is STEM education?

The term STEM education can be used in at least two distinct ways. STEM refers to science, technology, engineering and mathematics. STEM education can be an umbrella term that refers to education in the distinct subjects that make up STEM (Freeman, Marginson, & Tytler, 2015) - I will refer to this as categorical−STEM, c−STEM, where this is simply a category or class of curriculum subjects . However, STEM education may also imply an educational programme that offers coordination or integration within STEM subjects guided by educational aims reflecting STEM as a curriculum area with some common underlying essence. This might be considered ontological−STEM, or o−STEM, where STEM is understood as an entity with its own identify and characteristics (Chesky & Wolfmeyer, 2015) rather than just a 'container' category with no inherent qualities of its own. STEM encompasses the development of fundamental knowledge and also its application in addressing real world problems and meeting human needs.

The extreme version of o−STEM education would imply the collapse of STEM subjects within a single curriculum subject with its own identify, and which only draws upon specific skills and knowledge from the distinct STEM disciplines in accord to the need of the particular STEM topics and problems being addressed (*e.g.*, Figure 1, g). However, it is also possible to envisage other forms of o−STEM education where learning from the different STEM disciplines is coordinated (rather than integrated) to highlight and support learning about what is common to STEM - that is, topics within the different school subjects are scheduled to maximise the ability of teachers to help students make links between them. So, for example the science teachers would know what mathematics was taught and when, and would deliberately draw upon and reinforce it in science contexts. The mathematics teachers would know when students met different science and technology topics, and would be informed about the maths drawn upon in these contexts in class, so they could emphasise these applications. Technology classes would similarly draw upon coordinated teaching of topics in science. These would be two-way linkages with teachers knowing where and when the topics they taught would be drawn upon in the other subjects - so messages to students about such linkages could be reinforced from both sides.

There is clearly a spectrum of possibilities here (*e.g.*, see figure 1). A minimal approach might be simply sharing and using information about the schemes of work already being followed in other STEM subjects. Beyond this is the possibility of coordinated planning where teaching staff in discrete departments are prepared to compromise on what they might judge an ideal order of teaching when only taking into account considerations from within their own subject, to give students a more coordinated overall STEM education experience.

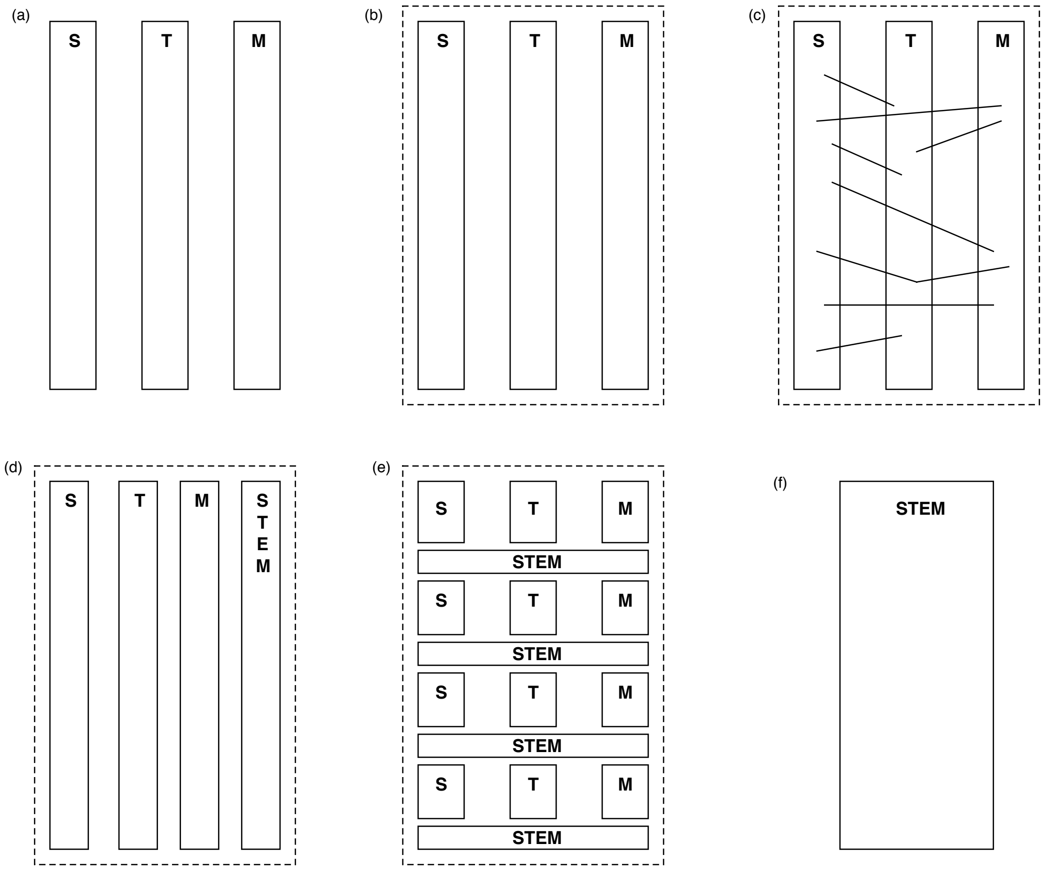

Figure 1. A few of the possible ways of understanding and organising STEM in the school curriculum: (a) as discrete subjects (e.g. science, mathematics, technology); (b) as discrete subjects, but within an acknowledged superordinate curriculum area; (c) as related subjects with explicit, designed linkages; (d) as discrete subjects running alongside a complementary STEM subject; (e) as discrete subjects feeding into regular collapsed STEM lessons; (f) as a distinct curriculum subject planned in its own terms.

It is also possible to collapse timetables across STEM subjects occasionally, or to build project-based STEM opportunities within the school year, whilst retaining the separate teaching subjects as the norm. It would also be possible to maintain STEM and separate STEM subjects within the timetable continually, but only to the extent that the global quota of time for STEM subjects allows. (So, for example, the members of a maths department could be asked if they were prepared to move from five 30 minutes classes per week to three or four, given that mathematics was also a core part of a complementary STEM subject running along side the maths classes, and which the mathematics teachers were partially responsible for planning and teaching. Similar requests would be made to the other STEM teaching departments.)

It should be acknowledged that the retention of distinct subjects in many curricular contexts does not simply reflect institutional inertia. The existence of learned societies and teaching associations, and so the preparation and development of teachers from within particular traditions, makes school subjects meaningful and relevant to teachers, even if not to all learners. Many science teachers, for example, will find a requirement to teach across the sciences makes demands on them, when their specialist training may be in a degree in a subject such as industrial chemistry, materials science, astrophysics or genetics. The demands of teaching within a recognised subject often challenge teachers, without asking them to coordinate (let alone integrate) with other subject departments where they have less understanding of the subject knowledge and disciplinary norms. Attempts to coordinate across STEM disciplines have highlighted many barriers to effective co-operation between different teaching departments (Archenhold, Wain, & Wood-Robinson, 1981; Barlex & Pitt, 2000). The present essay makes a strong case for the development of opportunities for integrative learning, but acknowledges that whilst this requires adopting o−STEM *at some level*, this does not necessarily imply collapsing teaching within one timetable subject.

The nature of disciplines

Disciplines are probably easier to discuss in abstract, than in concrete terms - given that the structure of academia is somewhat fluid, and so what comprises a discipline is open to interpretation. This is sometimes reflected in school timetable labels. The position of design as part of craft, and/or as part of technology, is one such issue. The shift from mathematics as an apparently unified school subject to distinct branches in upper secondary school (with labels such as pure, applied/mechanics, statistics, decision/discrete mathematics) might be another example. In secondary education in many countries, especially at lower secondary level (*e.g.*, 11-14 year olds), science is a teaching subject, although in some national contexts, or even within particular types of school within a single national system, biology, chemistry and physics (and perhaps earth sciences) might be seen as separate teaching subjects reflecting common distinctions in academia.

In effect the question of the extent to which STEM education should be o−STEM reflects debates in secondary curriculum policy seen in some countries in the 1960s-1980s when new courses in 'co-ordinated', 'integrated', or 'combined', science were introduced in place of separate sciences. Such debates raise questions about the extent to which the flavour of the distinct sciences should be retained as an explicit feature within a 'science' curriculum subject, and the extent to which it should be the nature of science *per se* - what is the essence of science, what makes an activity scientific - which should be a guiding principle in setting out what should be included in a school science curriculum. That question might also lead to consideration of whether aspects of psychology or geography or sociology or economics should be considered part of science for the purposes of constructing 'school science'.

In terms of the notion of o−STEM introduced above, these historical debates about the science curriculum (Jenkins, 2007) might be seen as in part about the question of whether school science should reflect what might be labelled 'o−Science' rather than 'c−Science' - a curriculum designed to give an authentic representation of science as a core cultural activity, rather than a reflection of the nature and core foci of the separate sciences. Such apparently esoteric considerations may have practical consequences in meeting the needs of gifted learners. Some attempts to develop courses in coordinated science, combined science, or integrated science have been considered to homogenise science in the way it is presented to students (sometimes even to the extent that learners may have a very limited notion of the different natures of specific science subjects at the point where they do become curriculum options that students are invited to chose for further study). In the UK context, separate science teaching was sometimes seen as more suited for academic streams, and less suitable for most pupils.

In principle, there is no reason why an o−Science approach should not be the basis of developing provision that would be highly challenging for gifted learners, but this of course depends upon how a curriculum is constructed. In the 21st Century English curriculum context, denying upper secondary students the opportunity to study separate discrete science subjects became linked with perceptions of 'dumbing down' of the curriculum. Government policy was introduced (Blair, 2007) in response to such concerns such that students in state schools demonstrating high attainment at age 14 would be entitled to study a separate sciences option during the following two school years despite the school subject having officially been 'science' since the introduction of a national curriculum (Taber, 2017).

Arguably, someone who took seriously the ideas of Thomas Kuhn (1974/1977) about the role of the disciplinary matrix within scientific practice might likely question whether it still makes sense to see biology, chemistry or physics as unitary scientific disciplines. Given the kind of elements that might compose (what Kuhn termed) a disciplinary matrix (see Box 1), it seems that in modern science disciplines are more specialised than the recognised core sciences. So perhaps we should see fields such as microbiology, synthetic organic chemistry, and condensed matter physics as disciplines: with their own paradigmatic elements shared among a scientific community. Similarly, to see 'mathematics' as a unified discipline ignores the organisation of the practices of actual research mathematicians.

shared ontological and epistemological assumptions
privileged theories, concepts, perspectives
core exemplars
routine instrumental and analytical techniques
preferred modes of representation
habitual specialist terminology and accepted abbreviations
expected reporting formats
valued conferences and journals for reporting findings

Box 1. Some elements of a disciplinary matrix

Certainly any understanding of the nature of a subject such as biology has to be historically located - modern biology post the Darwinian-synthesis, with its strong foci in areas such as cell biology, biochemistry and genetics, is not the same subject as the biology of the first half of the nineteenth century. Similarly, physics post-quantum mechanics (and relativity) looks very different to physics at the end of the nineteenth century which was considered nearly complete and exhausted by some scientists at that time (Badash, 1972). Even the core trichotomy of biology-chemistry-physics is surely to some extent (but see 'The significance of knowledge domains' below) an accident of history rather than a natural cleavage at intrinsic scientific joints.

Such philosophical questions are of more than academic interest if the curriculum is understood and justified in terms of the way different disciplines can offer complementary insights into human experience and culture as part of a liberal education to prepare young people to fully engage in their societies. The argument is that in a liberal democracy every student should be introduced to the major areas of the culture (Hirst, 1974). When such an education is effective it empowers citizens to be able to participate in wide ranging discussions across cultural domains. The kind of situation lamented by C. P. Snow (1959/1998), where 'educated' people are expected to be familiar with the works of, say, Shakespeare, Kant, and Beethoven, but it is perfectly acceptable to admit ignorance and indeed disinterest regarding the ideas of Darwin, Lavoisier and Bohr (or indeed Brunel, Tesla, and Lovelace) should not occur where there is a truly liberal education.

Curriculum integration *sans* subjects

Although one approach to curriculum suggests that all students should be introduced to the major areas of culture, and a subject-based curriculum seems to offer one way of ensuring this, it is of course quite possible to structure a curriculum that encompasses introductions to major areas of culture without explicitly basing it on academic subjects. Indeed one argument for working towards an integrated curriculum is that the traditional school practice of moving between clearly labelled and discretely timetabled subjects offers an experience that many learners find of limited relevance to their lives outside school. This is especially so for those who do not aspire to academic study post-school, or who are judged by their schools as unlikely to be suitable for such study.

Arguably school becomes more relevant and motivating, at least for these learners, when it is organised around authentic issues and problems. The themes may be chosen so that students still do meet disciplinary knowledge (Beane, 1995), but within contexts that are motivated by the current project: students still 'do' history or mathematics or literature, but as and when the subject offers a useful contribution to the current curriculum focus. This is a strong argument, and attempts to offer authentic projects as integrated (cross-)curricular foci can indeed be very engaging for students. However, this consideration is generally less salient when considering the needs of those students judged gifted, who - when suitably challenged - are often motivated by traditional school subjects, and are often happy to accept the formal structure of a subjects-based school timetable as a suitable framework for organising their learning. Here it is considered that the value to gifted learners of exploring more integrated approaches should be understood in terms of supporting their intellectual development rather than providing greater motivation to engage with school work *per se*.

The significance of knowledge domains

If the boundaries of the disciplines are to some extent historically contingent, it seems that there are domains of knowledge that may have a more definitive biological basis. It has been argued that during human evolution a number of domains of experience may have been established as part of the cognitive architecture of the human mind (Mithen, 1998). That is, particular realms of experience of major cultural significance may have come to be represented in mind through general features of human brain structure. So it may now be inherent in human cognition that as part of normal development people come to have somewhat distinct and compartmentalised knowledge domains relating to mechanics, biology and materials science (which might be considered to map to some extent upon the traditional academic areas as a kind of proto-physics, proto-biology and proto-chemistry). These domains are not considered as just themes identified from experience, or absorbed from the culture, but rather to be channelled in part by genetic predispositions. (That is, this has been selected for over a great many generations because it offered some kind of adaptive value to people when their thinking was channelled that way.) So young babies appear to have intuitive 'expectations' about some aspects of the behaviour of physical objects in the world before having sufficient personal experience to explain those expectations (Goswami, 2008). There are also strong commonalities on the way people in diverse cultures tend to parse the biota - as if the human genome has evolved to be biased towards certain ways of classifying living things (Medin & Scott, 1999). Young children also normally develop a 'theory of mind' (Wellman, 2011) that might be seen as a proto-psychology and which clearly has adaptive value for a social animal.

One well respected theory about cognitive development explains how the brain is able to construct mental representations of experience at different levels, through a process where representations at implicit levels of cognition (what might be labelled more 'primitive' levels) can be re-represented at other, more explicit, levels (Karmiloff-Smith, 1996). The most implicit forms of knowledge structures in the brain tend to be inflexible and function in a holistic way, and are not open to direct introspection. We only have indirect experience of them because their 'output' leads to perceptions and intuitions which (are experienced to) just appear in consciousness (see figure 2).

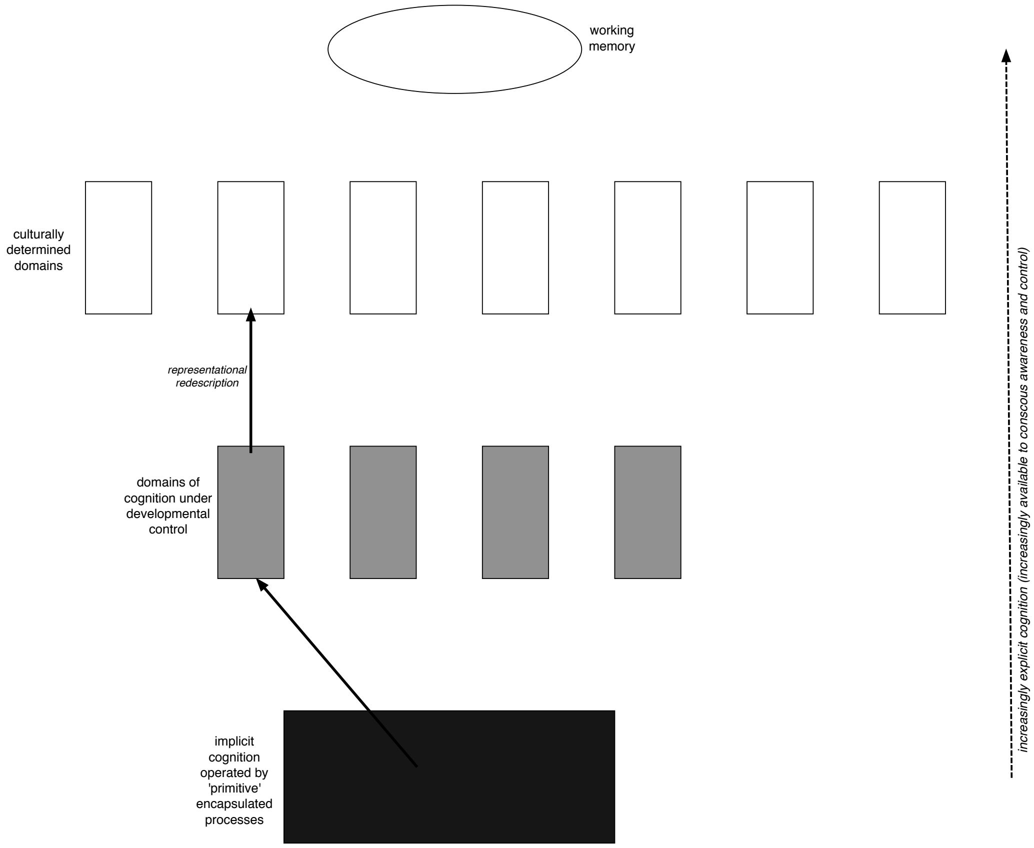

Figure 2. A simplified model of the human cognitive system showing levels and domains of cognition. The system allows knowledge representations at more implicit (*i.e.*, pre-conscious) levels of the system to be re-represented ('redescribed') at more explicit (accessible) levels.

The most explicit forms of knowledge are more plastic and open to conscious examination - allowing reflective and metacognitive thought. More explicit representations may be of verbal or imagistic form open to direct mentipulation (this is discussed in more detail in Keith S Taber, 2013). These different aspects of cognition might be considered to parallel other features of our bodies. If conscious explicit thinking is compared to the deliberate movement of our voluntary muscles, then implicit cognition is more akin to the muscular actions involved in the heartbeat or peristalsis. We are aware that our hearts beat and that food passes through our digestive systems, without needing to deliberately activate, or having ready control of, these systems. Yet while these different forms of cognitive representation are quite distinct, the system seems to have evolved so that a representation at a more primitive level can be represented 'higher' in the system where it can be subject to more deliberative mental action.

These ideas may seem familiar to readers who have studied the works of the psychologists Piaget and Vygotsky. Piaget (1970/1972) considered human cognitive development to have reached a stage of formal operations when the individual was able to form and operate on mental representations of existing mental representations. Whereas the younger learner needs to actually work with physical objects (which may be tokens for other objects), the mature student can imagine objects and mentipulate them within a mental workspace to model what would happen in the physical world. Vygotsky (1978) understood cognitive development in terms of the interplay between spontaneous conceptions developed from direct experience of the world and academic concepts acquired through social interaction and the use of systems of representation (*e.g.*, language). The outcomes of such development were melded concepts that both reflected what could be directly experienced and were also able to be conceptualised and communicated through the shared conceptual tools of the culture (Keith S Taber, 2013). In terms of figure 2, the level of culturally determined domains may be considered to be constructed through processes of the representational redescription of representations at more implicit levels deriving from direct experience of the world, moderated by learning through the symbolic systems of culture such as language. So, for example, a student's conceptual representation of physics derives from the interaction of teaching and prior conceptions formed from the interpretation of direct experience of the world (Keith S Taber, 2013). The common outcome is that student understanding is not a partial representation of the taught domain (somewhere between ignorance and expertise) but an idiosyncratic hybrid of canonical and alternative conceptions (Taber, 2014).

This ability of the brain to not only represent aspects of experience of the external world, but also to represent representations themselves such that these re-representations can be adopted for new roles in cognition, seems to work in a 'horizontal' as well as a 'vertical' sense, in that representations in one domain of experience may act as sources of (re-)representations that can be explored in other domains (see figure 3). That is, humans are able to construct metaphors, similes and analogies. A metaphor has hidden meaning - as when it is said that a cell is a production plant. A cell is obviously not the same as an industrial plant, but the metaphor suggests there is a way that a cell can be considered to function like an industrial plant. For example, this particular metaphor might be intended to be understood in terms of the cell apparatus including complex structures that produce great numbers of different protein molecules in the way that a factory might include a range of production lines producing multiple copies of objects of some kind.

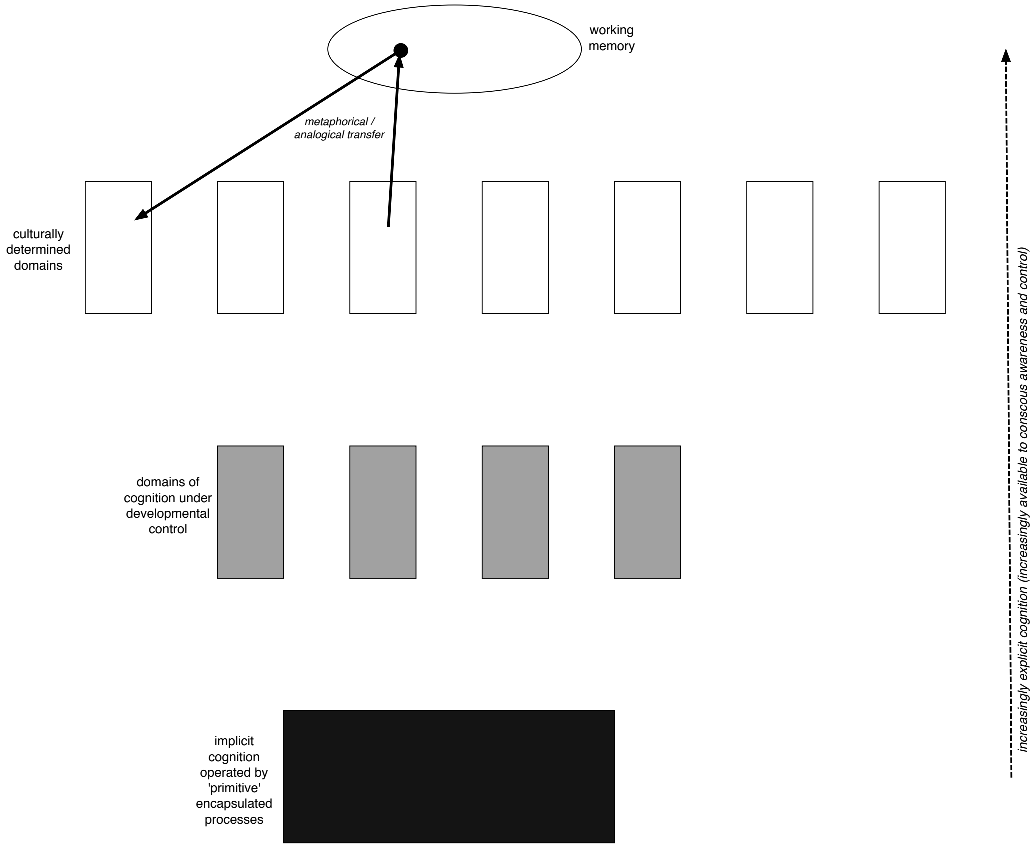

Figure 3. A simplified model of the human cognitive system showing levels and domains of cognition. The system allows knowledge within a particular domain to act as a model for new knowledge in a different domain.

A simile differs from a metaphor in having an explicit comparison - such as saying that DNA is *like* a set of instructions for building an organism, or that atomic energy levels function *as* steps of a ladder, or that implicit cognition is *like* the muscular actions involved in the heartbeat or peristalsis. Potentially a simile may be used like a metaphor in the sense of leaving the nature of the comparison implicit: the nucleus *is* the brain of the cell; the mitochondria are *like* the power plants of the cell. However, often similes are not left unexplained, but rather elaborated upon: for example, Evolution could be considered to be like an arms race, because...

Analogies are more formal comparisons still, as they point out a potential structural isomorphism between two systems, by showing the mapping between the two structures (Gentner, 1983). So, the rate of production of products in a simple chemical reaction (where the reactants are not being replenished) is analogous to the decay of current flowing during capacitor discharge. This analogy can be explored in terms of which features occupy parallel, analogous, roles in the two systems - for example the way in which current flow reduces the potential difference (a driver of current flow) in the latter case is parallel to the way that product formation reduces the reactant concentration (a driver of the reaction) in the former.

In each case, these devices rely upon the creator of the metaphor or simile or analogy recognising similarity between what on the surface are quite different objects or systems. Examples ('the atom is like a tiny solar system') may be learnt through teaching or other social interactions. However a metaphor, simile or analogy that is original for the individual who has not had the similarity pointed out to them requires an act of creation. Asking students to develop novel metaphors, similes or analogies requires them to be creative, and can engage and challenge gifted learners (Taber, 2016a).

Creation

Koestler recognised a similarity across humour, artistic creation and scientific discovery, in that these different activities relied upon the ability to make connections across diverse events, contexts or domains - what he referred to as a bisociation (Koestler, 1978/1979). From a constructivist perspective, where new learning builds upon existing thinking, and where perception is channelled (and so constrained) by existing cognitive resources (Taber, 2014), it would be expected that novel ideas must always be derived in some way from existing mental resources. So the ability to form connections between previously distinct mental 'content', and the capacity to - in effect - project conceptions into different cognitive domains and explore whether such a mapping leads to useful novelty, offer possibilities for potentially powerful creative thought.

Metaphor, simile and analogy, offer one form of linking between domains where one domain acts as the source, and one as target for new knowledge. Hooke's transfer of the notion of the monastery cell to the magnified image of plant tissue he was seeing down a microscope, Meitner and Frisch's notion that the behaviour of an excited liquid drop might act as a model of atomic nuclear behaviour, Buckminster Fuller's application of structural features found in organisms to the design of buildings, and Kyoto and colleagues' recognition that Buckminsterfullerene had a geometry that reflected a soccer ball, are just a few examples of how creativity can involve linking or transferring between different domains. However, bisocations can also involve connections that subsume previously considered unrelated material within a new common framework or overarching concept (see figure 4). This has been particular important in the development of science.

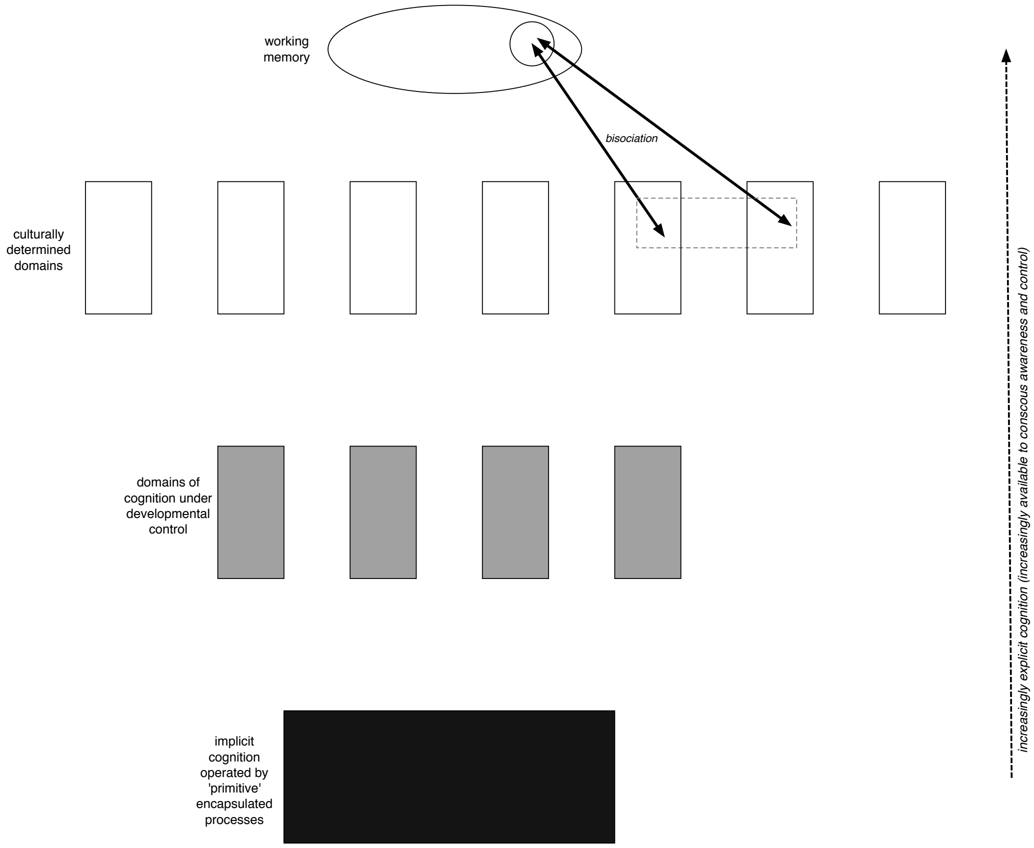

Figure 4. A simplified model of the human cognitive system showing levels and domains of cognition. The system facilitates forming links between concept areas and domains so that these can be subsumed within more integrative structures.

Conceptual integration and science education

Science is sometimes considered a value-neutral activity as the job of the scientist is to discover how nature is, not pass judgement on it. Yet scientists bring aesthetic judgements and metaphysical positions to their science (Keith S. Taber, 2013). As the world experienced is clearly extremely diverse and complex, a science that is not to be largely futile also depends upon a metaphysical commitment that the observed diversity emerges from simplicity - that all of the great complexity of the universe could be reduced to a modest number of basic principles in action. So science values (i) fundamental principles that have wide application and (ii) subsuming diverse phenomena under increasingly fewer basic categories (*cf.* figure 4).

Some examples will suffice to illustrate these points. A few conservation principles such as that of energy and momentum are found to be widely applicable. Newton's law of gravitation was heralded as 'universal': his achievement was not discovering gravity (it had been noticed), but recognising and demonstrating that the same basic process applied on earth as in the heavens. The diversity of the material world is understood as emerging from fundamental types of substance, the elements, of which there are limited number. Moreover the periodic table of elements is itself explained in terms of a few types of object (electrons, protons, neutrons) and principles (four quantum numbers). Evolution offers an explanatory scheme potentially consuming myriad observations about types of living things, variation within and between species, over space and time, and so much more. Maxwell was held in high esteem because he posited a small set of fundamental equations that could be understood to unify electricity, magnetism, and the kind of radiation now known as electromagnetic. This 'kind' itself subsumed what was previously a range of separate types: gamma rays, X-rays, ultraviolet, (visible) light, infra-red, microwaves, radio waves. That Einstein spent much of his later career looking for a Grand Unifying Theory that would subsume electromagnetism with the other fundamental forces reflects how much scientists value unifying the distinct - reflecting the scientific value (or GUT feeling, perhaps) that more encompassing theories are of highest worth.

So, science values ideas that can integrate and codify large bodies of knowledge. It has been mooted that a suitable demarcation criterion for an authentic science education is that it supports learning for conceptual integration (Taber, 2006). Yet in some contexts school science has been charged with being too much concerned with learning across a wide range of topics so that it becomes more about mastering a great of information than developing deep understanding. This can readily happen when biologists, chemists and physicists all come to curriculum planning with a long wish list of 'essential' topics in their own domains. Certainly there are concepts associated with the disciplines which everyone should learn something about before leaving school (perhaps natural selection, atomic theory, and conservation of energy would be good candidates) - but there are also many topics traditionally taught in school science lessons which whilst of interest and relevance within the disciplines, are hardly essential for all future citizens, nor likely to compromise later advanced study if their introduction is delayed. An authentic science education would better be judged by its ability to support students in conceptual integration across diverse topic areas, than in offering a completists' introduction to potential curriculum topics.

Making integrative connections across STEM

If conceptual integration should be a demarcation criterion for science education - prioritising the search for links between science topics and concepts - then cross-disciplinary link-making is surely the *raison d'être* for STEM education *qua* STEM education. Engineering and technology are distinct from science but both rely upon it, and provide major rationales for investment in scientific research. For many scientists a primary motivation may be to learn about nature - and a civilised society should support the growth of knowledge. But at a time when the global community suffers from environmental crises, and where - for example - millions die from potentially curable diseases, the justification for supporting research with substantial sums of public money also has to be more pragmatic. Science has to offer new materials, more energy efficient technologies, more sustainable agriculture, medical advances, and the like, to justify high levels of public investment.

Mathematics, like science, needs to be valued in its own terms, as a means of producing new knowledge within its own domain. Yet the justification for asking students around the world to spend years studying mathematics cannot be the tiny proportion who go on to become professional mathematicians and so contribute to the development of mathematical fields of knowledge. Mathematics education has to in part support the potential applications of mathematics to other fields - and this will be especially important in science, engineering and technology. Within the school curriculum, science and technology offer major opportunities to show where mathematics can be applied within authentic problem contexts. A similar argument can be made about computer science and informatics - subjects with major applications in science, engineering and technology.

Yet it is well recognised that school learning can be of limited transferability (Lobato, 2006). Students may learn about dietary components in biology without readily relating this to the food they consume. Students may fail to be able to apply the most basic mathematics in other lessons. Students may even feel that what they learn in one science class has no relevance in other science subjects (Taber, 1998). Students commonly tend to compartmentalise learning, so that 'What is learnt in chemistry, stays in chemistry'. Yet advances in the world of science and technology often rely on the ability to transfer ideas between domains. It has been argued that the Wright brothers realised they did not have to make an aircraft intrinsically stable - as their competitors tended to assume - as long as the pilot had sufficient control: an insight based on their experience of working with bicycles (Johnson-Laird, 2005). (A bicycle being ridden by an experienced cyclist seldom falls over, even though when not being used the cycle has to be secured or it will topple.)

Here of course we might consider the gifted learner to be an exception. One of the qualities sometimes associated with gifted learners is just that ability (that seems to be so lacking in many students) to look across traditional subject and other barriers. So we would expect gifted learners to have greater competence at applying ideas learnt in one lesson, in another. A student who spontaneously suggests to the teacher that *an idea learnt in another subject might be relevant and useful in this one* is rare in many classes. Indeed such suggestions may be uncomfortable to many teachers when they are being asked to comment on something outside of their own specialist domain. Students may even be advised that this is a (whatever) lesson, and here we study (whatever), and such syncretic notions do not belong. If gifted students are able to see connections, and make links between disparate topics and subjects then a curriculum that inherently compartmentalises subject matter may act as a kind of mental straight-jacket. Such a curriculum denies all students opportunities for more authentic applications of learnt concepts and skills, and denies gifted learners opportunities to develop their potential for forming original links and demonstrating conceptual synthesis.

STEM education therefore has a major potential role in offering authentic opportunities and contexts for experiences that do allow genuine cross-disciplinary work. However, this is only the case when STEM education is organised as what was labelled above as o-STEM education - which can recognise the specific contributions of individual STEM disciplines, but provides a curriculum where these disciplines are allowed to interconnect to support both authentic applications and cross-disciplinary fertilisation of thought. Such a curriculum has both vertical and horizontal threads - spaces for learning about the knowledge domains and ways of thinking within disciplines, but also spaces for authentic learning activities that can draw upon knowledge and skills from across the STEM disciplines (and sometimes beyond).

Conclusion

In summary, there are various ways STEM education can be understood and organised within the curriculum. In terms of supporting high level cognition and substantive developments in conceptual understanding, what is important is that the curriculum is organised in a way that provides opportunities for learners to make creative links between areas of subject matter. The ability to spot potentially fertile linkages, explore and develop them; and to evaluate their value, either as sources of novel understandings within a concept area, or as syntheses that offer better integrated - and so more efficient - conceptualisations across concept areas or knowledge domains, is a marker of giftedness (see figure 5). It is also an ability necessary for finding creative new solutions to problems facing society and indeed humanity globally. STEM education, when seen as more than just a collection of distinct school subjects, is ideally placed to offer opportunities for recognised gifted learners to hone, and for latent gifted learners to develop, this ability.

Figure 5. Decisions about how to organise STEM education within the school curriculum may impact on the extent to which teaching can offer integrative learning opportunities suitable for challenging gifted learners.

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