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Chapter 1

THE VICARIOUS AND THE VIRTUAL: A VYGOTSKIAN PERSPECTIVE ON DIGITAL LEARNING RESOURCES AS TOOLS FOR SCAFFOLDING CONCEPTUAL DEVELOPMENT

Keith S. Taber** and Xinyue Li
Faculty of Education, University of Cambridge, Cambridge, UK

ABSTRACT

Digital learning resources are commonly employed to support formal and informal learning, sometimes as a complement to the teacher, but sometimes as an alternative. 'Flipped learning' is increasingly being adopted as a progressive pedagogy, such that students are expected to learn new ideas and principles from course material (often using digital platforms) before coming to class to apply this learning. During a time of pandemic, schools may be closed and teachers asked to teach virtually as students remain at home. During such a public health emergency, more

* Corresponding Author's E-mail: kst24@cam.ac.uk.

responsibility for directing teaching may pass to parents or to the learners themselves, who may seek out virtual learning resources as the basis for home study. This chapter considers the characteristics of digital teaching resources capable of facilitating independent learning of a kind that can support the development of new capacities. It draws upon Vygotsky's ideas of how higher-level intellectual skills are developed, and his distinction between learning in general and more substantive intellectual development. Vygotsky's theories about teaching and learning offer a solution to the classical learning paradox (that without knowing what it is we do not yet know, we cannot recognise it and so come to knowledge) as in this perspective learning is not understood as coming to some ideal absolute knowledge, but rather sharing in aspects of culture that have already been acquired by others (such as a teacher or more experienced peer). One key idea is that the learner initially experiences new competences vicariously, through participation with the more advanced other. That is, teaching that is merely a matter of an expert telling a novice what to do is insufficient to support development. Rather, development requires the learner to actually experience success in an area of activity that is currently outside their competence - through what is termed 'scaffolding'. Culture (including academic concepts and intellectual skills) is therefore 'transmitted' through social interactions where those with expertise (such as teachers) allow novices to vicariously experience their successful actions. This raises the question of the essential characteristics of a digital learning tool that can go *beyond* supporting the exercising of existing capabilities, to act as a virtual tutor and provide learning experiences that can scaffold substantive development without needing the concurrent direction of a teacher.

Keywords: digital learning resources, flipped learning, metacognition, scaffolding learning, zone of proximal development, self-directed learning, PhET interactive simulations

INTRODUCTION

In this chapter we consider the characteristics of digital learning resources that can support student development by going beyond simply offering sources of information, to engage learners in activities that can scaffold more substantive learning.

To exemplify these principles, we describe and characterise some of the digital tools available to support learning. (Our treatment applies across much of the school curriculum, but we will draw some of our specific examples and illustrations from science learning.) In particular, we discuss two common scenarios. One is the phenomenon of flipped learning, as when a lecture is recorded and made available digitally as preparation for a subsequent class in which students are expect to demonstrate learning acquired from the digitally recorded lecture.

The other is the use of 'apps' that are available for smartphones and tablets (such as the iPad) or other digital platforms, when used by students to learn informally. Our initial focus here was on students who will undertake self-directed learning to follow personal interest, or to augment activities prescribed by a teacher, for example when revising for school examinations. However, the writing of this paper coincided with the global COVID-19 coronavirus pandemic, and we were writing in 'lock-down' at a time when schools in many countries were closed to most students and so teachers had been asked to substitute on-line learning for face-to-face teaching. In this situation parents (in the case of younger learners) and students themselves took more responsibility for directing learning, and in many cases turned to on-line resources to support home schooling during the period of relative isolation. Whereas teachers may have appropriate professional knowledge and skills to evaluate the educational value of potential learning resources (even if they were often being asked to prescribe activities at short notice with limited time for undertaking research into the options), parents and school children have a much more limited basis for making critical judgements. Whilst the COVID-19 emergency is an extreme public-health event, and we very much hope it will have ended by the time this chapter is published, it has shown the potential importance of the availability of virtual learning resources which are designed from a pedagogical perspective. This is the focus of our discussion.

A Programme for the Chapter

In this introductory section, we introduce themes that will be drawn upon through the chapter. The first of these is a 'first approximation' model of two distinct kinds of learning that has particular implications for the nature of teaching. We also offer an introduction to the ideas of 'digital' learning and teaching.

We then discuss some of the key ideas of the Soviet psychologist Lev Vygotsky that have become very influential in educational thinking. In particular, we consider Vygotsky's notions of how development can be supported by mediation in a learner's so-called zone of proximal development through forms of scaffolding. We then apply Vygotsky's perspective (and the notion of two classes of learning) to a long-standing question, the so called 'learning paradox'.

This leads to a consideration of what is termed 'flipped learning': a pedagogic strategy which has become very common in some higher education contexts, but which may be more problematic when adopted in school level instruction. Our discussion of flipped learning draws, again, upon the distinction between different classes of educational objectives related to the different types of target learning. From this we reflect on the nature and role of the teacher - at whatever level, and through the different modes of instruction that digital tools enable (that is, face-to-face or at distance - if perhaps face-to-screen-to-screen-to-face; synchronous or asynchronous, directly or through the construction of learning resources).

We then offer a brief overview of the range of digital tools now available to learners in many educational contexts. This highlights how distinctions between hardware and software, and between tools that are seen as educational or having other purposes, are not always straightforward. It is clear that the 'landscape' of digital tools with potential for supporting teaching and learning is vastly different from when many current teachers entered the profession.

This then provides the basis for a discussion of the extent to which digital tools support the development of learners in terms of facilitating the vicarious experiences that Vygotsky thought were so important to allow the development of 'mind in society' - that is in accessing the intellectual achievements of, and so becoming a full member of, a culture. We discuss two examples of digital tools developed to support science learning. One example adopted a pedagogic model to inform the development of sequences of interactions intended to guide students along particular learning pathways when using the resources outside the classroom (and so without immediate access to a teacher). The other example is based on a design adopting strategies for 'implicit scaffolding' within resources to nudge the learner towards learning goals whilst giving a sense of open enquiry.

Two Types of Learning?

As will become clearer later in the chapter, we are making a broad distinction between two types of learning, which might be labelled assimilation and accommodation (Glasersfeld, 1990). By assimilation, we mean the learning of material that can be added to and fitted in with prior learning (without that prior learning requiring any substantive adjustment). By accommodation, we mean something more substantial (and potentially disruptive). We explain these terms with some examples from science learning.[1]

A student who already knows there is a category of living things called molluscs, might seek to find some examples, and may come to learn that oysters, squid and snails are molluscs. A student who knows that in science there is a system of official units used in measurement might be aware that electrical current is measured in physics, and wonder what the unit would be - and may learn that this is amperes. A student may have noticed that in

[1] These terms are used in Piaget's (1970/1972) theory of development, as being parts of a process where assimilation of new material into existing structures always leads to some degree of disequilibrium and is followed by accommodation to achieve a new equilibrium. The meaning here is not fundamentally different: rather we are following a tradition that as a first approximation distinguishes learning that requires relatively cosmetic restructuring from that which needs a more substantial change in the existing structure. This is a simplification, for as we suggest later in the chapter, the degree of restructuring needed to accommodate new learning might better be understood as a continuous dimension.

chemistry classes the teacher refers to most groups of the periodic table by numbers, but tends to call one group 'the halogens'. The student may decide to see if any of the other groups have such names - and discovers the terms 'the alkali metals', 'the alkaline earths', and 'the noble gases'. In all these hypothetical cases we can imagine the learner already has a framework in which they are aware, or suspect, there are potential lacuna that could be filled. Although 'filling' these 'knowledge gaps' is not entirely trivial - one must have some tools to do an Internet search: a device, an Internet connection, a web-browser, and some basic skills in carrying out a search - the learner knows what it is that is being looked for, and - assuming the sources they access are accurate - has a good chance of knowing when she finds the answers she is seeking.

However, much learning is not of this kind. Students may not know what it is they are meant to be looking for (see the discussion of the learning paradox, below), as they may lack a suitable knowledge framework into which to assimilate new elements of knowledge. A student who had heard of evolution and decided to learn more about it may come across material about Lamarck's theory of the inheritance of acquired characteristics, and not realise that this is a historical model that is not canonical. (Many students find aspects of Lamarck's theory more intuitive than the theory of natural selection taught in school science, so learning about the non-canonical account is likely to act as a learning impediment when the student later meets the topic in school.) Or, they may come across material from young earth creationists arguing that evolution is only a theory, and that it actually has very little support; and that it is contradicted by a vast amount of scientific evidence, and is indeed rejected by many scientists - there is a good deal of such material in the public domain despite this being contrary to mainstream scientific thinking.

In science there is a vast literature showing both (a) that before instruction children tend to hold many alternative conceptions inconsistent with science and (b) that (in part, consequentially) it is common for students to interpret teaching in non-canonical ways (Taber, 2009). So, for example, in science the fungi are a distinct kingdom of living thing from plants (or animals), yet in everyday use fungi such as mushrooms and toadstools *are* considered plants. So, a student asked to research the species names of plants who came across examples of fungi is likely to include these in her assignment, as her existing thinking guides further learning. This general phenomenon (misinterpreting information and so forming new, or reinforcing existing, alternative conceptions) is widespread even when teaching takes place in a classroom where a teacher is interacting with students (and so getting feedback on their thinking).

Science teaching is then often about developing whole new ways of thinking about aspects of nature that may be found counter-intuitive. So, for example, a student learning about forces and motion is likely to approach learning already holding notions that need to be challenged in teaching (Watts, 1983), and where research shows that even skilled classroom teachers aware of this context find it difficult to bring about long-term conceptual change - such that high levels of alternative conceptions are found among those having completed school and college level courses (Caramazza, McCloskey, & Green, 1981). Such change requires a restructuring of thinking, not just addition of a new fact or example.

Our distinction here may be considered a first-order model, as clearly learning does not fit neatly into such a dichotomy: rather, there are degrees of restructuring needed in different learning episodes. Yet it is clearly the case that learning that can be fitted into existing frameworks (such as learning that metals generally have properties of ductility and sonority - *once* a learner has a well-established concept of metals; or appreciating that force will be a vector, *after* the learner has a clear understanding of the difference between scalars and vectors) is less problematic than learning a major new skill or concept area, or developing a new, more advanced, scheme - such as, for example, the shift between seeing acids as substances that release hydrogen ions in aqueous solution to considering acids as electron pair acceptors. That there are matters of degree is linked to the idea that in instruction the teacher both breaks up complex new learning into manageable learning quanta that can be used to build a new framework, and looks for points of attachment with the learners' past learning and experiences (using analogies, models, metaphors and so forth). Learning of complex scientific ideas has been found to be a process that is interpretive, incremental and iterative (Taber, 2014): and science teachers need to actively manage the process from the perspective of the desired target knowledge (Taber, 2018b).

To provide a context for discussing how instruction may be achieved through learners engaging with digital learning tools, we will below consider the nature of learning, and of teaching, in the light of a theory that has been especially influential in education - Vygotsky's learning theory - and the idea of scaffolding learning which has been based on it. This analysis leads us to consider:

1) how digital resources may help students in the processes of assimilation and accommodation
2) the potential for scaffolding learning supported by digital resources compared to scaffolding learning by direct interaction with teachers — something with clear implications for the role (and so design) of digital tools in teaching and learning, such as, for example, the structuring of flipped learning.

Digital Learning and Digital Teaching

There is little doubt that the widespread availability of digital information technology, both in the classroom and in the home, has changed the landscape of educational technology considerably. In many countries, the traditional chalkboards in classrooms first gave way to projection screens and then interactive boards that allow both the ready presentation of prepared material and the real-time engagement with, and modification of, those materials. Not only can digital teaching resources be constantly modified and updated in response to changes in curriculum specifications, but also in response to a teacher's experience of using them in the classroom and developing understanding of their subject. Indeed, where teaching is seen as an interactive process relying on the teacher planning lessons according to assumptions about the students' prior knowledge, understanding and relevant experiences (Taber, 2005), and so accordingly constantly seeking feedback during the lessons through formative assessment to inform the teaching (Taber, 2014), modern technology allows copies of prepared teaching materials to be amended 'in situ' during the lesson to fine-tune them to accommodate the particular class being taught at that moment (Hennessy, Deaney, Ruthven, & Winterbottom, 2007). Teachers starting work in the profession today probably do not appreciate how some of their more experienced colleagues (such as the senior author of this paper) would earlier in their careers have had to retype a hand-out or worksheet from scratch each time that they wished to make any substantive change to it.

A virtual learning environment allows ready access to diverse formats of tool (see our brief survey below), including many that can be modified by teacher and/or student, and which are accessible at any time. Where some older teachers may still feel that digital resources are not as real as 'hard copy', new entrants to teaching must wonder how the large-scale processing of trees into the single-use, readily damaged, classroom resources that was characteristic of schools just a few decades ago could ever have seemed environmentally justifiable and sustainable.

Digital devices are ubiquitous in many parts of the world. The once state-of-the-art computer station in the corner of the classroom (itself a major innovation in its time) has given way to laptops, and tablets - such that for many schools there is now an assumption that each student has and uses an iPad or similar device; and many students routinely carry 'smart' phones that keep them permanently networked through the Internet. (There is clearly a very important issue in relation to the uneven access to this technology - both between and within national contexts. Our analysis of the affordances and limitations of different tools is all very well for those lucky enough to have the choice of employing them: but that is by no means everyone, even in some of the wealthiest nations).

This has raised the dilemma for schools of deciding whether the negative impacts of the smartphone as a source of distraction during lessons outweighs its potential use as productive tool in the classroom:

> Many students use their smartphones to access on-line teaching materials, organise team-work to solve problems and to share knowledge and information. Smartphones can be turned into powerful and affordable learning aids for many students. However, if they are not utilised properly they can also create a serious interference for learning. (Anshari, Almunawar, Shahrill, Wicaksono, & Huda, 2017, p. 3072)

Of course, the fountain pen was once the tool for much classroom mischief, as well as being the means for note-taking and essay writing - yet pens were not banned from schools because of their potential for misuse. The Internet supports the World Wide Web (www) which offers virtually instant access to seemingly unlimited quantities of information (and, of course, misinformation), and puts extensive libraries of material within reach of students based on a simple search.

Teachers can also use the Internet to share resources within a community of peers, and readily customise those they download for their own specific teaching contexts. Whilst this certainly raises issues of intellectual property and scholarly norms (not everything on the www is presented as open source and/or copyright waived; not every teacher who uses the Internet to access materials is careful about checking on copyright or acknowledging sources), it offers an immense potential for division of labour.

As one example, the PhET Interactive Simulations project has a website hosted by the University of Colorado at Boulder that offers, free of charge, a wide range of simulations designed to support the teaching of mathematics and science (Wieman, Adams, & Perkins, 2008). From a cost-benefit analysis perspective, it is possible to justify putting considerable time and effort into developing such resources because they are accessed by a great number of teachers and learners from around the world. These resources have consequently been designed in accord with a carefully researched and developed conceptual framework (Podolefsky, Moore, & Perkins, 2013), as we consider in our Discussion section below. A lone teacher who has responsibility for teaching, perhaps, twenty or more hours of lessons each week, across a range of classes and topics, and who had to design all of their own digital resources would (even assuming they had the programming know-how) take many years to build up a library of quality simulations for use in classes.

The Challenge of Utilising the Affordances of Digital Tools

However, it is widely recognised that the full potential of digital technology is not automatically realised in educational practices (Deaney, Ruthven, & Hennessy, 2006). Those who design resources may lack the subject knowledge, pedagogic expertise or classroom experience to produce materials that support effective forms of teaching. Therefore, it can be hard for young learners with limited understanding and knowledge to identify which digital resources are intellectually valid and pedagogically reliable. Teachers and technical support staff in schools will often trial a number of educational apps available in the App Store, before selecting those they see as most useful, and introducing or adopting them in lessons, or recommending students to try out certain apps in out-of-class contexts. However, it can be difficult to employ this reviewing process to examine other types of digital resources from online platforms (e.g., those students may come across in the results when using a search engine). Teachers may not have the time (or confidence) to learn how to best use new tools, and often may simply use the technology provided to them to carry on teaching as before, changing the media but not drawing upon its potential affordances.

In this chapter we will consider this topic from the perspective of Vygotsky's theory of learning and development. In particular we will consider the use of digital learning resources *outside of* the classroom, either under a teacher's direction (as in what is often called 'flipped-learning'), or by students in self-directed (or parent-directed) study. Vygotsky understood teaching in relation to wider cultural development, and as a fundamentally interactive process where a teacher (i.e., someone who takes on this role in some shared activity, not necessarily a professional teacher) helps a learner work in what is termed their zone of proximal development (ZPD), through a mediating process referred to as scaffolding. This raises the question of how digital learning resources can best support teaching, especially in an asynchronous mode - when the teacher is not engaging with the student (immediately or at distance) at the time when they are working with those resources. In particular, this raises the question of how digital learning resources can be designed to offer learners the kind of 'vicarious' experiences that Vygotsky suggested are most productive.

VYGOTSKY, LEARNING AND DEVELOPMENT

Vygotsky (Лев Семёнович Выгóтский - known in English as Lev Semionovic Vygotsky - 1896-1934) was responsible for introducing into educational discourse both the commonly-used, but rather awkward-sounding, notion of 'the zone of proximal development', and the equally widely discussed principle that has become known as 'scaffolding' of learning. As these concepts are central to the application of Vygotsky's ideas, we will briefly introduce them before considering Vygotsky's wider thinking.

Learning in the Zone

The notion of the zone of proximal development derives from a spatial metaphor where Vygotsky imagined a kind of multi-dimensional 'phase space' relating to the potential competencies of a learner. If one imagines such a space representing all the potential competencies a human being might acquire (being able to solve a quadratic equation, understanding syllogism, being fluent in Welsh, knowing the names of the chemical elements, playing chess, understanding the rules of cricket, designing electronic circuits, and so on) then each of these competencies would be represented by one dimension in this phase space, reflecting the potential degree of competence from having no awareness of the competency at all, to the highest level of expertise.

Whilst these dimensions are continua, it is useful to consider that for any human being at some moment in time that space can be divided into three regions. One of these regions comprises all those competencies the person has already mastered, where they can perform well without support. This is referred to as the zone of actual development (ZAD). By contrast, the region where a particular person has no competency at all - such that they are not in a position to make any substantial contribution to the task even as a fairly junior member of a team (we might think along the lines that someone asked to supervise their work would think it was easier and less effort to do the work for them than to have to give frequent, precise and detailed instructions to produce slow and inaccurate outcomes) is known as the zone of distal (far) development (ZDD).

Between these two zones, and often of most interest to educators, is the zone of next, or proximal, development (ZPD). This represents those competencies the person has not yet acquired, but which prior learning and development has prepared them to be ready to tackle. Most significantly, this is the zone where although the person is not yet ready to achieve anything unaided, they can make productive progress with support - something like an apprentice ready to start constructively taking on some tasks under supervision, with suitable guidance. When working with and observing someone further advanced along the dimension of competence the learner is able to vicariously experience what success in that specific activity is like, and they can make some progress in suitably structured tasks, with advice and feedback.

The term ‘guidance’ is perhaps especially appropriate, as the novice is guided along a particular path towards expertise, rather than completely left to their own devices in an unfamiliar landscape. Guided, that is, rather than carried or frog-marched: the learner has to experience the journey willingly, as a tourist who is making her own choices, but informed by others who are already familiar with the local territory and so can suggest the best use of precious time.

Two important points about the three-zone model are perhaps not immediately obvious. One is that although there is a qualitative difference between the zones (no competence, some competence when supported, autonomous competence) each of the zones still reflects a range along the dimension. A student facing a task which is in her ZDD may be more or less 'distant' from being ready to learn about that task; two students working on a task that falls in the ZAD of both may show different levels of expertise and performance. The second point is that a person's position within this 'space' is not static, for as they learn they move along these dimensions, and as, consequently, the ZAD, and the ZPD expand, more tasks are brought from the ZPD into the ZAD, and from the ZDD into the ZPD (Taber, 2018d).

Scaffolding and Fading

If follows, therefore, that for some specific learner a task that requires a particular competence they have not yet acquired may, due to learning of prerequisite knowledge and skills, move into the ZPD. Initially the individual will need a good deal of support (demonstration, advice, instructions, exemplification, etc.) to make progress, but as they start to develop competence they will need less support until, ultimately, they are able to work autonomously without support (at which point the ZAD has expanded to include this activity).

The term scaffolding is used to refer to support that is offered by a teacher (or parent or more experienced peer) which has been designed to match the learner's state of development: that is, just enough structuring of activity through support to enable them to begin to be able to successfully engage in the activity and start developing some competence (Taber, 2018d). As the learner progresses, less structuring and support is needed, and indeed matching the level of scaffolding to need offers optimum support for making good progress (Taber, 2011). An important aspect of scaffolding then is 'fading' scaffolding at just the right rate to maintain the correct balance of challenge and success. In practice, judging the best level of scaffolding is very difficult (Taber & Brock, 2018) and so relies on teachers using frequent formative assessments (Black & Wiliam, 2003) to make judgements about fading scaffolding.

Vygotsky and Development

Vygotsky was interested in development at different levels, from how an individual acquires a new capability, to how societies develop through creating culture (Taber, In press). Of course, a society does not exist without the individuals who make it up, and who contribute to its development. Vygotsky recognised that whilst some aspects of an organism's development were largely under genetic control, this was not the case with important aspects of human development.[2] Rather, higher-level intellectual skills would not develop in isolation, as this depended upon the individual experiencing particular aspects of culture that could support that development (Vygotsky, 1978).

This goes beyond the trite assumption that an individual human baby nurtured to adulthood physically - we can imagine some science fiction scenario where the immediate needs of the child, let us call her Roberta Crusoe, are provided by complex machines that function without any need for symbolic (e.g., linguistic) engagement with the child - will not automatically know what a hypotenuse is, nor intuit Pythagoras's theorem, and will not work out for itself that hydrogen is the first chemical element. Clearly, the child could only learn these things by being taught in some sense. This is surely so, but is in a sense a fairly trivial (if also in some ways profound) conclusion.

However, Vygotsky goes further than that, to suggest that the kind of higher-level intellectual *skills* we associate with adults in our society simply would not develop. It is not just that our isolated child will not have the language to talk about right-angled triangles, but that *the level of abstract thinking* needed to understand what is meant by 'the square of the hypotenuse' would not develop. Vygotsky's contemporary, Jean Piaget (1970/1972), also acknowledged that cognitive development required interaction with the environment, and that included the social environment. However, Piaget's model suggested a unitary pathway of broad cognitive

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[2] This distinction may be obscured by the use of the term 'genetic' in Vygotsky's writings to refer to origins (which could be cultural rather than due to genes) more generically (i.e., relating to *the genesis of*) - similar to how Piaget termed his programme 'genetic epistemology'.

development which all humans would potentially follow. By contrast, Vygotsky recognised the contingent nature of culture, developing in a dialectic manner (in a similar way to how a learner's conceptual learning is strongly channeled by their current ideas), such that it was possible for development to have qualitatively different end-points in different cultural contexts.

Yet it is also clearly not *always* the case that people only know and understand what they do because they are taught by others (either directly or through representational systems - be they Egyptian hieroglyphs, textbooks, on-line lectures, or digital simulations of the photoelectric effect). History clearly shows us that culture evolves over time, and, in some regards at least, makes progress - something Vygotsky himself was very interested in. For example, it seems indisputable that medical science today is more advanced than it was in 1820 or 1920 or even 1970 - so this implies that individual human beings must in some sense be able to go beyond what they can learn from others. (Vygotsky himself died in 1934 aged 37, from tuberculosis - now a curable disease.) However, those advances considered great breakthroughs never happen in a cultural vacuum: no one gets to the level of understanding of an Einstein in any established field without considerable support (Gardner, 1998).

One of us has previously noted "that which affords one to develop as an adult mind operating in some particular society at some point in its history would not be available to a lone epistemic subject learning directly from interactions with the physical/natural (non-social) environment" (Taber, In press). Roberta, our hypothetical machine-nurtured child, will develop personal conceptions of the world, and may demonstrate a fair level of ingenuity, but will not postulate the Higgs boson, or appreciate that a small proportion of her generic material suggests there were some Neanderthals amongst her ancestors. She will develop some useful intuitions about how to operate on physical objects in the world (although these intuitions will very likely be strictly inconsistent with Newtonian principles of physics - as suggested above, most people's intuitive physics is non-canonical when compared with scientific accounts), and classify plants in her environment on some scheme (perhaps including some fungi alongside edible plants -

which, though taxonomically incorrect, may be a perfectly sensible practical approach), and will no doubt develop some conceptions about materials that could be understood to relate to canonical concepts such as fluidity, density, elasticity, brittleness, opacity and the like - but she will not develop equations of motion, infer the reactants in photosynthesis, nor define Young's modulus. This is not just a matter of not having verbal language to use such terms, but more fundamentally of not having achieved the cognitive development to conceptualise at this level of abstraction from immediate experience (Vyshedskiy, Mahapatra, & Dunn, 2017).

That some people achieve greatness in various fields raises the question of the extent to which this reflects something special about that person, or the support they found in the environment, or a matter of 'luck' of being alive at the right place and time for their 'field' to recognise their potential (Gardner, 1998). What is clear is that any potential Michaelangelos, Tolsoys, Maos, or Bachs who were not supported to develop and hone their skills by their cultural environments are lost to history (along with their potential works) - something pointed out by the poet Thomas Gray (1751): "But Knowledge to their eyes her ample page / Rich with the spoils of time did ne'er unroll."

Humans have a creative capacity. We can synthesise, and can form analogies, and deconstruct and rebuild - but all of this requires acquiring higher-level intellectual skills that are only developed after being initially accessed vicariously when we are invited to share in activities that induct us into our society's cultural wealth (Luria, 1976).

OVERCOMING THE LEARNING PARADOX

The learning paradox is an argument that suggests that learning should not be possible, or at least, that learning anything truly new should not be possible. If we seek knowledge we do not know, then how will we know when we find it? And how will we know how to go about the search if we do not know what it is we are looking for? Despite having an impressive pedigree, and being taken very seriously by some philosophers, this does not seem much of a paradox to many people working in education, or, indeed, to many scientists.

A Hypothetical Learning Challenge

There probably are circumstances where the learning paradox is sensible. Consider, for example, that you had an elderly Aunt who was terrified of infections, and never left the house or accepted visitors. Over the years she had sent you many presents and cards inscribed with standard greetings ('Happy Birthday' and the like), and you had reciprocated, but you never really got to know her. Now you learn she has died, and left you, her (apparently) favourite niece, a small gift in her will. She has, you are now informed, an impressively large collection of ceramic ornaments. She wants you to have one of these as a keepsake, and as you were her favourite she would very much like you to have her favourite piece. But, sadly, she does not give any further description. You enter her house for the first time, find many pieces of similar value, displayed with similar prominence. You know you are looking for her favourite piece, but… You seek knowledge of your aunt's favourite ornament, but have no way of knowing if you find it. At least not if we take 'knowledge' to have a traditional sense, such as true, justified, belief (Goldman, 1995).

You could, of course, take a guess and you might be right. But a guess is not a belief, and guessing does not support strong epistemic justification. Plato offered a way out of the paradox by suggesting we all have a good deal of eternal knowledge that is accessible to our immortal souls - and so we recognise truth when we see it as a kind of remembering of this innate knowledge. We recognise the form. If there was a form of Aunt's favourite ornament, and it is known to your soul, you would recognise the eternal form in the piece. (I do not think Plato was suggesting such specifics - but perhaps you would identify the piece because you and your Aunt both recognise the form of beauty or grace or some other general notion). Logically that works, but not everyone believes in an immortal soul (and those that do may not believe it has access to the forms), and there are major debates about how much innate knowledge people have, or indeed, given our genetic make-up, could have.

Perhaps the piece you like most will have been her favourite? Perhaps you share taste, and that seems as good a basis as any for making a choice. You could decide it was the favourite and from henceforth it will be known as her favourite piece - this is a kind of conventionalism. The social group agrees (Piaget, 1932/1977), as when it is agreed that a cricket innings is over once ten wickets are taken (it could have been nine or eleven; there could have been four balls in an over; the wicket could have only had two stumps…), but falls short of knowledge of the Aunt's own choice as most people would understand 'knowledge'.

Yet often when we seek knowledge the circumstances are rather different from this. Perhaps your aunt also left you a piece of jewellery which is in a particular locked box. The solicitor tells you that, unfortunately, your aunt had 'no end' of locked boxes (being concerned about burglars as well as germs) and so there is a whole pile of keys, any one of which could be the right one for that particular box. In one sense we have a parallel situation. Auntie has not left any guidance on which of many apparently equally likely candidate keys might open the box - at face value it could be any one of them, and we are not better off than we were with all those ornaments. Yet here we can do an empirical test. We simply and carefully try different keys in the lock until one of them opens the box. At the start of the 'experiment' we do not know which key opens the box, and have a whole set of comparable hypotheses, but we do know that the key we are looking for will open the box. We have a criterion. Once we find a key which does open the box, we do then know that was the key we were looking for. So, there is no learning paradox there.

When Does the Learning Paradox Apply?

In our introduction we suggested it may be useful to consider learning as being of two broad types, assimilation into an existing framework, and accommodation where there is (to borrow an idiom) no round hole into which it would already be obvious a square peg will not fit. In the case of assimilation, we have a kind of lock and key situation - there is a knowledge substrate which is 'shaped' to accept only a correctly configured knowledge element, thus acting as a catalyst for learning. (We will revisit that metaphor of catalysing learning, later in the chapter.) Of course, this is not a perfect comparison, but usually in assimilation the existing state of knowledge considerably limits the 'degrees of freedom' available for viable options. If a learner sought to find out the capital of France, and concluded that it was Marseille or Berlin we might be disappointed, but if they instead told us they had discovered the capital of France was Marie-Anne Lavoisier or Eric Cantona or gram-negative bacteria or Plato's republic we would be quite perplexed about how such a differently shaped factoid-peg had become lodged in that particular knowledge cavity.

The traditional paradox works for metaphysical truths - things that are not open to empirical investigation. Science seeks true knowledge of the world, but most scientists would consider that this is more akin to our second example - we can do tests and so we get feedback from nature to tell us when we right. Of course, science is more complicated than that. There are always some *a priori* or metaphysical commitments underpinning any empirical programme of science (Taber, 2013). There is also underdetermination - that any data we collect can fit a range of theories. So perhaps several of Aunty's keys unlocked the box, and the one we use to open the box was actually for a different box, and strictly we have found the 'wrong' key. An instrumentalist response would be that a key that opens the box *is* a right key - it is good enough, even if not a perfect match. Philosophers of science disagree about whether we should settle for that kind of knowledge (Rudolph, 2005; Scerri, 2010).

In education we tend to have an even clearer situation. The student, let us call her Barbara, is meant to learn about, say, how to recognise cell organelles using a microscope. But the student does not know how to recognise such organelles. The student peers through the eyepiece and sees various patches and smears and blurry lines, but does not know what she is looking for - so how can she find it? She may know she has to focus the microscope, but she has no idea how to do that, or what difference it will make - certainly an in-focus specimen looks different to an out–of–focus specimen, but unless you know which is which, how do you know what to aim for? For that matter, as she does not know what a microscope is, how can she be sure she is using the right instrument?

This is of course not a realistic scenario as Barbara will not just be let loose in the laboratory without prepping and guidance – this is more akin to what might happen if our fictitious Roberta Crusoe was suddenly transported into a school biology laboratory when there was no one else around, and peered down (what we know is) a microscope at (what we know is) a preparation of stained onion skin. Roberta would have no way of making good sense of this experience.

Even Barbara is unlikely to initially see anything of note down the microscope without specific support from someone who already has access to that aspect of culture (Charlker, 1982; Nivala, 2013). She has to learn to position and illuminate the slide on the stage and to focus both the instrument, and her attention on the input from the eye peering into the eyepiece (when the brain's natural tendency is to pay more attention to the brighter, more expansive, and meaningful, field of view of the other eye). Even then, she has to learn to discriminate the messy, complex, organic jelly into discrete structures - something like how a Picasso might impose an unrealistic structure on a scene to pick out and foreground specific objects. Just being given a microscope and a slide and the instruction to identify organelles would be an almost certain recipe for failure - a task in Barbara's ZDD - too far from her current competences (her ZAD) to be a realistic challenge.

A class of thirty biology students with no previous experience of microscopy, and no knowledge of the components and structures of the cell, but just left to get on with identifying and drawing cell organelles, is something of an impoverished version of the clichéd infinite number of monkeys with typewriters. Perhaps one of these students might succeed, but that seems unlikely, and there would be broken slides and damaged microscopes (as well as confused and frustrated learners) to show the folly of this type of approach. This scenario reflects an extreme version of 'discovery' learning. It has been well-critiqued by those sceptical of constructivist approaches to teaching who sometimes label it minimally guided learning (Kirschner, Sweller, & Clark, 2006). Of course it is a straw man (Taber, 2010c). The frequency with which real teachers, even those who consider themselves as good constructivists (Driver & Oldham, 1986), would proceed in this manner is comparable with the frequency at which those hypothetical monkeys would churn out typescripts of Hamlet!

Optimally Guided Instruction

Effective teaching requires optimally guided instruction (Taber, 2011), which supports learners in the steps of the learning process - so that they are channelled towards the ‘right’ discoveries. (A bit like one of Aunty’s keys having a tag attached marked ‘for my favourite niece’). Barbara would be shown photographs and line drawings of the type of cell she was to view (the former representing what she might hope to see down the microscope when it was correctly set up, and the latter representing what she should slowly learn to abstract into the highly idealised biological drawing). She would practice using the microscope with low magnification and more readily interpreted objects (perhaps crystal grains, pollen, the head of a sewing pin) before attempting to see the structure of a cell under high magnification. She would also have the input of the teacher – deciding, for example, at what point it ceased to be counterproductive to allow Barbara to rotate the focus knobs back and forth rather than focusing the slide for her; asking her about her drawing and giving feedback on its acceptability in terms of the target version.

And that is the key in educational work: there is usually a teacher who already knows what the target knowledge is, and can guide the learner through demonstration, explanation, instruction, questioning, critique, praise - and so forth. Moreover, a good teacher does not go through this repertoire of inputs on autopilot, but is constantly monitoring and making decisions about when to intervene in the student’s learning activity, how best to intervene, and how much to intervene.

Digital Tools to Guide Learning

This is at the core of the question about how to produce high quality digital tools that can support substantive learning. It is not so difficult to produce tools to reinforce existing learning, or even tools to teach facts that extend current knowledge within an existing conceptual framework (i.e., what we have labelled assimilation). Here the student can work in the ZAD where they are not developing substantially new skills or conceptual structures.

An application that includes images and characteristics of all the known moons in the solar system can help a student learn more about those moons - assuming she already had a basic framework of understanding about the solar system and what moons are. However, it would be very difficult for a person lacking that cultural context to make any sense of the application - we can imagine someone from the ancient world, or perhaps from an isolated Amazonian tribe today, who thinks of THE moon as some kind of Goddess companion to the Sun, and the planets as just some of the many stars in a heavenly realm that the Gods have provided as lights in the night sky. Even if we assume they could make sense of a tablet screen (which, like the microscope image, is a representational system that has to become familiar before it can be interpreted, something usually achieved through the mediating input of someone already having been inducted into this aspect of the culture) they would not understand what the images of planets and moons and orbits were meant to be - they would have no relevant referent in their cultural system.

That is not a prejudicial evaluation. In a parallel way, the Amazonians would find our visitor with an iPad could make little sense of much of the highly valued cultural knowledge which all inducted members of the tribe have mastered, and which tends to be more relevant to survival and well-being in the rainforest than knowing whether Jupiter or Uranus has more moons - for example vital discriminations between different plant species that look 'much of a muchness' to our digital native. "That which affords one to develop as an adult mind operating in any particular society at some point in its history" would not be fully available to an epistemic subject arriving from a different culture.

The Role of Metacognition

For that matter, it should be relatively easy to offer tools that can support substantive learning of advanced autodidacts. So, for example, a science teacher should be able to learn some new science material, even if in an unfamiliar domain, as they should have not only a strong background of foundational concepts, but also the metacognitive skills to direct, monitor, reflect upon, and evaluate their own learning. This is not limited to teachers, but would also apply in parallel ways to lawyers or engineers or medical practitioners. Autodidacts do not (seem to) need teachers, but few children in the early school years could manage to make much good progress in the curriculum without teachers.

We can explain the development of metacognitive skills through Vygotsky's theory. According to Vygotsky the learner first experiences new skills in the social plane, that is, as part of action demonstrated by, or shared with, others. In time they develop competence through this vicarious experience (that is, though sharing in activity directed and carried out by others), and so the skills shift to the personal, intra-mental, plane. What is initially modelled for a learner in the social space then becomes represented internally, in their mind. So, when the actions of a teacher monitoring learning, breaking down complex tasks into manageable quanta, explicitly comparing where the learner is (what the learner has so far achieved) with a target, are shared publicly, and so experienced vicariously, they support the development of internal (mental) resources.

This suggests that we can, as a rule, expect a greater degree of this self-monitoring and self-directing of learning in university students than teenagers, and a higher degree of it among teenagers than primary school children. Accordingly, when digital learning tools are expected to support informal or self-directed learning in students, we need to ask more of the digital tools when they are intended for school age students rather than undergraduates or professionals. This may explain why flipped learning seems to be most popular in university settings.

THE PARADOX OF FLIPPED LEARNING

One pedagogic strategy that has become widely adopted in recent years is what is known as 'flipped learning' (Seery, 2015). The 'flipping' refers to a supposed reversal of the usual sequence of formal learning. A caricature of traditional teaching could be that students come to class where the person considered a relative expert, the teacher, explains the basic ideas and demonstrates the basic skills, and then students work on exercises to apply those ideas or skills. The teacher shows students how to find the roots of quadratic equations, or explains the basic principles of natural selection, or sets out a canonical account of the causes of the industrial revolution (or whatever), and then the students are given tasks that test their understanding of this newly acquired knowledge, and that give them practice in applying these ideas - which is intended to rehearse and reinforce what the learners are meant to take away from the teacher's input. Often these tasks will be set, at least in part, as 'home-work', work to be done in private study to follow up the classroom session - so without the immediate support of the teacher. If such reinforcement is to be accessible to all the students in a class working without mediation from more advanced others, then it needs to be within the ZAD for all the students.

The Khan Academy and the Flipped Classroom

Undoubtedly one factor in the popularity of the idea of flipped learning is the work of Khan Academy, based on a notion of a 'flipped classroom'. Salman Khan started his journey of flipped teaching by posting short videos online to help his cousin Nadia with mathematics learning. His tutoring videos are short, and so usually end before students become distracted or fatigued. These videos have become popular online learning resources and have attracted many young viewers, and so Khan then found the Khan Academy, which is one of the largest online platforms with flipped learning resources.

The philosophy supporting this initiative is not simply one of making available a library of short video lectures, but an alternative to traditional schooling. Whereas in the school system students are necessarily organised into classes, usually grouped by age cohort, and taken through a largely common curriculum via a single path, Khan's notion of the flipped classroom has particular characteristics (see Figure 1) and involves students finding their own pathway through the learning material at their own pace, such that the audience for a particular video lecture could comprise of a diverse range of students both in terms of any (or no) formal curriculum and, for example, age (Parslow, 2012).

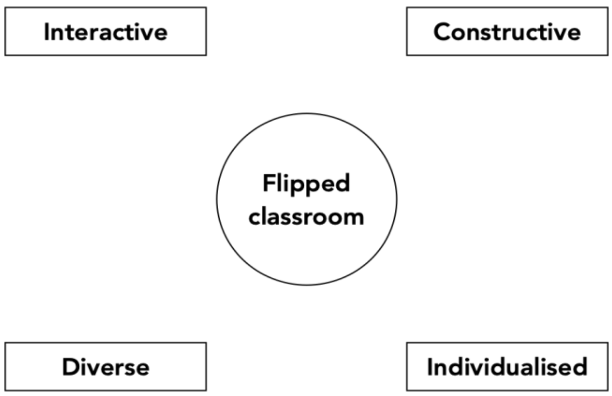

Figure 1. Some of the characteristics of Khan's model of a flipped classroom.

Khan also opened an actual, physical, Khan Academy as a kind of laboratory school where the flipped classroom can be enacted in full-time education (Montague, 2014) - an experiment reminiscent of earlier progressive ventures such as the Summerhill School that adopted a free school model of students deciding when (or if) to opt into particular classes (Stronach & Piper, 2008). Whilst the Khan Academy videos certainly do provide a library of resources that can be used in self-directed learning, they are also widely used by teachers and college lecturers directing their students to view a particular video as a primer for classroom learning as part of a flipped learning strategy within a conventional curriculum.

Why Is Flipped Learning Becoming More Popular in Higher Education?

Khan Academy videos tend to be short, and Khan's style is to offer a conversational presentation rather than a didactic formal lecture. Digital resources of this kind can be used very flexibly. However, there is also a model of flipping whole lectures from the lecture hall to a video library,

> In one of [flipped classroom pedagogy's] common forms, students acquire background knowledge on a topic by watching video lectures online before coming to the lessons, while they can engage in student-centered and active learning activities to further develop their higher-order learning around the topics in school. (Wong & Cheung, 2015, p. 69)

The rationale for flipped learning is an argument that students actually often most require support from the teacher at the point when they are expected to apply the ideas. They may have listened to the teacher's presentation, and copied their notes and examples, without internalising the key principles that will allow them to actually understand the new ideas well enough to apply them. (Of course, as discussed below, a skilled teacher would expect to engage learners actively in thinking about their presentations so that this would not be the case.) Therefore, it is argued, the sequence of exposition by teacher, then application later alone, needs to be reversed ('flipped'). Instead, students should come to class having already been provided with the basic information, so that class time can be used in undertaking exercises, solving problems, and engaging in challenging ways to apply the learning. Rather than squandering most of the class time with the teacher simply presenting information, that presentation should be set as preparation for class, and then the teacher can spend more time supporting students in applying the learning.

Flipped learning has always been possible in school or university contexts. Indeed, it has been common practice to set readings ahead of class that are meant to provide background to the session, even if this has not commonly replaced the teacher exposition. The possibility of setting, say, Chapter 7 of an adopted text, as required preparation, and then using class-time for activities that apply the assigned material was a possibility wherever schools or students could afford textbooks. Now it is possible to substitute a wide range of alternative resources, in particular, digital video files, for textbooks.

Flipped learning seems to have become quite popular in some higher education (university) contexts, but - in this more substantive sense - is less widely utilised in the school sector. It is easy to suggest reasons for this: school teachers may feel they cannot rely on all the students completing set preparation (where university lecturers can more justifiably take the view that any student who neglects to complete such work takes responsibility for the consequences); also, university lecturers may have more time and professional support for preparing resources, such as filming lectures.

Limitations of the Lecture as a Mode of Teaching

This may also reflect a common difference between school teaching and much (if certainly not all) university teaching. Many university programmes are still nominally based around lecture courses, and often the lecturers employed to give the lectures, do just that (i.e., lecture). Lectures can be well-structured, informative and even entertaining, but prototypically are one person talking and everyone else listening. Even when lecturers break up their presentations with short activities, and encourage students to ask questions or make points as they seem relevant (rather than waiting for a private audience at the end of the class when the moment is gone, and when students may feel that they are now encroaching on the lecturer's 'own' time) the general pattern is of the expert offering a presentation of content to the class.

School teaching cannot generally be like that, as when typical classes of school children are presented with long periods of exposition, no matter how knowledgeable the teacher, and how skilful the presentation, there is usually minimal learning. Indeed, a common challenge to new entrants to teaching, often graduates moving from university contexts where they have experienced many lecture courses based on being talked-at for periods of 50 minutes or even longer at a time, is to appreciate just how little teacher-talk typical school children can pay attention to, and concentrate on, before becoming distracted or fatigued.

That is not to say that classes which are based on teacher talk - *superficially* like a lecture - are always poor lessons. Skilled teachers can find ways to keep students' attention over extended periods, but only by building in pedagogical techniques to explicitly link what is being taught to students' interests and experiences, and by making the talk conversational so students are actively engaged and not just listening - and so are constantly providing feedback to the teacher on how the talk is being understood (Taber, 2018b). In school teaching it is the student's responsibility to pay attention and be open to learning, but it is the teacher's responsibility to help students understand the teaching. That is a kind of social contract in the classroom. Teachers who just 'drone on' for long periods, regardless of how students are making sense of teaching, default on the contract and can no longer expect students to continue to pay attention and make the effort to learn (just as, arguably, students who make no effort to engage in class default on the right to have the teacher later explain everything to them). Even when a teacher is highly skilled in such 'dialogic' teaching techniques (Ruthven et al., 2016), it is still sensible in school teaching to base most lessons on short periods of teacher-led talk interspersed with student activities, especially group activities where students are asked to talk about the ideas they have been presented with.

Effective Teaching

So good classroom teaching is staccato in nature, moving between different episodes (Mortimer & Scott, 2003) - some led by the teacher, some in other modes of engagement, and where the 'teacher talk' segments should not be one-way communication of information, but rather a learning conversation that is interactive and dialogic (that is, engaging with the learners' perspectives and ideas) even when it is the teacher doing much of the talking. Clearly it is difficult to see how such lessons can be readily 'flipped'. Certainly, a thirty-minute video of the teacher talking about the subject of the class could be set as preparatory work, but no matter how good the teacher's subject knowledge and exposition, this does not substitute for the teacher-led segments of a quality lesson where a good teacher is constantly monitoring student understanding and adjusting the presentation accordingly in real time. No matter how high quality a video lecture is in technical terms (image quality, sound quality) it fails to be teaching in its fullest sense.

So, what about university lectures? Adult learners are physiologically very similar to children in many respects. They can usually concentrate for longer, and may typically have greater motivation to learn than many school students (but of course many school children are highly motivated to learn, and some university students become disengaged or distracted) but, just as school children, their learning is hard-won as they need to make sense of teaching and to understand how it relates to prior learning. Yet, to some degree, every student in the lecture room starts with a somewhat different set of background knowledge, relevant experience and examples, take on vocabulary, appreciation of metaphors and analogies, skills at decoding diagrams and graphs, and so forth. Even, if by some fluke, a lecture was *perfectly* honed for one of the students in the room, it would almost certainly not be quite so perfectly matched to the different, unique, sets of interpretive resources that the other students have available.

So, if a lecturer is just that - someone who comes into the room, checks with a student's notes just where she had got up to at the end of the previous class, and then proceeds to talk and display materials for an hour - then it makes sense to film that lecture and in future simply ask students to watch the lecture - and then use class time to build upon that initial familiarisation with the material. If the teacher simply talks on, regardless of the students' reception of the presentation, then it should make little difference if an actual lecture is filmed, or the script read to an empty room (indeed arguably there would *be* no difference to the lecture!) Hopefully many lecturers would baulk at that description of their lectures - as it has long been recognised that students deserve and need more than a recital of a script (Taber, 2010a).

Video Contributions to Blended Learning

We are maintaining a distinction here between flipped learning, where the digital resource replaces a teacher's live exposition of a topic to a class, and the use of video-recorded presentations in blended learning. Blended learning involves,

> a deliberate 'blending' of face-to-face and online instructional activities, with the goal of stimulating and supporting learning…combinations of face-to-face and online teaching activities have been found to offer several new opportunities for optimizing learning…in which technology is used to design instructional activities that were previously hard to organize. (Boelens, De Wever, & Voet, 2017, p. 2)

Now, clearly, substituting a video of a teacher teaching another class for that teacher teaching this class does not obviously use technology for instructional activities that were previously difficult to organise (rather, it may free up more class time for other activities). Yet there may be occasions when video lectures *could* meet this definition.

So, for example, a course may involve some face-to-face class time spread over one or more academic years, which is necessarily limited because course members are geographically spread apart - with only occasional opportunities to physically meet for classes at the academic base, supplemented by episodes of distance learning. Perhaps, more tellingly, a course may have different guest keynote lecturers who allow their lectures to be recorded to build up a library of contributions - allowing courses to include contributions from participants who cannot be readily invited back. Usually in these contexts, a guest lecturer's input (either in person, or recorded) would be followed-up by some other kind of activity directed and/or mediated by a course tutor.

Similarly, in MOOCs, Massive Open Online Courses (Liyanagunawardena, Adams, & Williams, 2013), which may sometimes have students enrolling from anywhere in the world, there is no possibility of students attending a class physically for face-to-face sessions, and so any video-lectures incorporated into a MOOC are not being used to flip classroom and home-study activities.

Implications for Digital Lectures

So, a good lecture will be customised for the class, and will be approached as a performance playing to that day's house - and so even when based on the same set of lecture notes it will be a unique enactment, responding to different audience cues, each time it is given. This raises the question of whether a lecture given by a more skilful lecturer who approaches teaching in this way will make for a better digital lecture resource. If the lecturer does make adjustments for particular students and classes, then whilst this improves the lecture *as given*, it likely interrupts the flow of the lecture *as filmed* when viewed by a different class. (That is, the more the lecture is like 'real teaching', perhaps the less it works as a flipped assignment.) So, to summarise rather bluntly: a poor lecture is a good candidate for being filmed for flipped learning (as little of much value from the classroom experience is lost); a good lecture likely has interactive elements that actually mitigate against it working well as a virtual learning resource - even if perhaps being a more entertaining spectacle. The implication being that, whilst video presentations can have some part to play in effective flipped learning, more interactive resources are needed (Taber, 2010b) unless much of the follow-up class is simply to be spent going through the lecture and helping students understand what they have watched.

The situation in school teaching is similar - but more extreme. No one (surely?) would suggest filming a school teacher working with a class, and then setting that as viewing for future classes as an alternative to re-staging the class anew with the subsequent cohorts. Not unless that school teaching was *simply lecturing* to school-age students, in which case it is likely not good school teaching, and so no more likely to make good educative viewing for future learners. Effective teaching resources for flipped learning therefore need to offer the kind of interactive elements that good school teaching (and more effective university lectures) have built in:

> most learning resources bought by schools are intended for use under close teacher supervision. Yet interactive software offers the promise of being something that can support learning with minimal teacher involvement: something learners can use in the library, or at home, freeing up the teacher to focus on other students, or allowing the teacher more time to spend on other topics or activities. (Taber, 2010b, p. 44)

What Makes a (Real or Virtual) Teacher

It seems then that if we wished to characterise a good teacher then this would encompass a number of features. Almost by definition, the teacher would have already mastered relevant learning material - abstract concepts, cognitive skills - that the learners have not. The target learning lies within the ZAD of the teacher, but outside the ZAD of the learner. However, the teacher not only has such competencies, but also a fund of professional knowledge that has been called pedagogical content knowledge (Kind, 2009). She has an explicit mental model of the relevant competences such as target knowledge, and has given consideration to how these can be built up in suitable ‘learning quanta’ through a sequence of steps - a specialised subject knowledge *for* teaching (Taber, 2020). This model will be applied in conjunction with another mental model which represents the particular learners' starting points - what they currently know, understand, and can do. This model is seldom entirely accurate, but is applied in an interactive way - that is, the teacher in effect poses a conjecture about the step the learner is next ready to take, and then tests this, using feedback to update the model of learner competences, and so inform a revised conjecture (Taber, 2014). If the initial conjecture proves to guide effective action on behalf of the teacher, then the model will soon need to be updated because the learner will make progress. If that progress occurs more readily than anticipated, then that can inform the size of step that might be tackled next. If the original conjecture proves to be over-ambitious, then revision may involve interjecting a new intermediate step towards that first proposed.

However, this is not just a matter of differently scaled steps in some linear progression: learning is seldom from a neutral starting point towards the target outcomes. Certainly, in science learning at least, it is very well established that learners commonly begin studying a topic with alternative conceptions that are inconsistent with canonical target knowledge, and/or with intuitions which do not match scientific accounts of the world (Driver, Rushworth, Squires, & Wood-Robinson, 2013). Moreover, whilst some of the ideas that students bring to class are widely shared, others are idiosyncratic (Taber, 2014). The teacher is aware of this, has knowledge of the most common learning difficulties and knows to look out for indications of misunderstanding of scientific concepts. We could say a lot more about this, but the key point is that effective school teaching is not only based on strong subject knowledge, but also on detailed pedagogic knowledge which allows teaching to be interactive and nuanced in real-time by collecting feedback from learners that informs the next teaching moves.

Students may become teachers in out-of-class learning contexts since they often engage in self-directed learning. However, they have not mastered relevant learning material or the pedagogical content knowledge like the (professional) teachers in the classroom; so, for example, they will not be able to appreciate the nature of their ZAD and (especially) ZPD. Digital resources being used by students therefore need to act as tools in place of 'more knowledgeable others' to scaffold the learning. Consequently, it becomes important not only for teachers, but also parents and students themselves, to understand how to evaluate which of the many accessible resources are meaningful and potentially educative for particular learners.

Implications for Digital Resources

We would expect the most effective digital teaching tools designed to support learning when a teacher is not present (and so able to monitor and intervene) to have some of this degree of interactivity that teachers demonstrate in the classroom, even if it seems unrealistic at this time to expect an app to be fully enabled in this respect. The degree to which this is necessary will also relate to the extent to which learners have already internalised (from the modelling provided when working with teachers) metacognitive skills that enable them to monitor and re-direct their own learning. There would seem to be a number of relevant features, then, at work (see Figure 2):

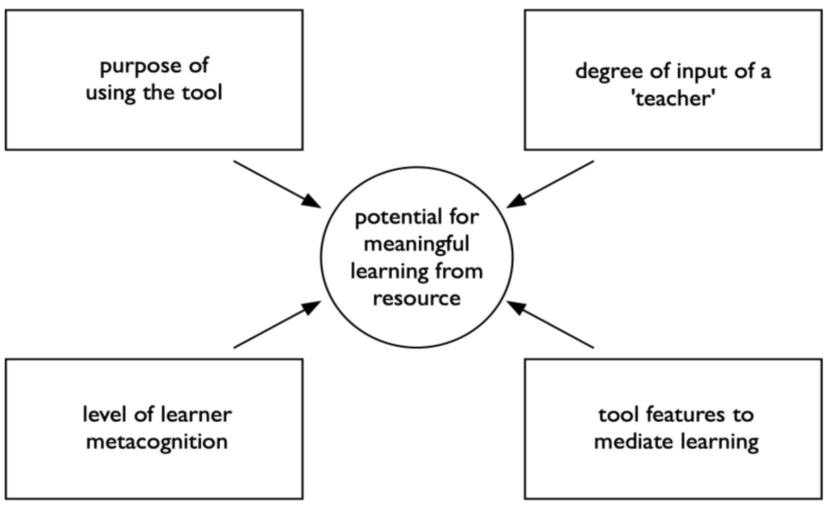

Figure 2. A range of factors determine whether a tool such as an ‘app’ can effectively support learning.

1) The purpose of using the learning tool. Whether learning is entirely self-directed for the student's own personal interest (when success might be judged purely in terms of whether the learner feels she has learned from the activity) – or, otherwise, *the degree* to which the activity is intended to support learning of formal school curriculum: when it matters that what is learnt matches targets set out in formal specifications, and that understanding of concepts is canonical and matches curriculum models (e.g., simplifications) of disciplinary knowledge.
2) The extent of the involvement of a human teacher (where the learning is curriculum-related): has the teacher given instructions in how to use the tool, and guidance on how to get the most out of it - or is the learner just left to make what they can of engaging with it.
3) The metacognitive sophistication of the learner - to what extent are they able to access and refer to curriculum specifications, plan their use of the tool, monitor what they are learning from it, and evaluate the match of actual learning to specified target learning.
4) The affordances built into apps to monitor student use, offer hints and feedback, and channel activity towards intended learning goals.

Clearly these must be considered together. An app to help a dinosaur enthusiast learn facts about lots of dinosaurs does not need to be as sophisticated as an app to support learning about how homeostasis occurs in the human body. An app to support an undergraduate revise details of organic reaction pathways need not be as interactive as one meant to teach a school student about Newton's laws of motion. An app intended to be used in the classroom whilst the teacher is present can be forgiven limitations that very much matter for unsupervised home study.

It is also important to consider whether an app is up to date. Some apps are updated regularly to fix bugs and develop new features; these apps offer more current learning opportunities than those being updated irregularly or never being updated at all after the initial release. We will now consider the design and affordances of some of the digital tools available that can support self-directed learning with this framework in mind.

TOOLS FOR SELF-DIRECTED SCIENCE LEARNING IN SCHOOL-AGE STUDENTS

Students often engage with self-directed learning in out-of-class contexts. Various online and offline resources can be adopted to support students' learning. These digital devices, apps, and web-based platforms can be conceptualised as tools. Tools can mediate between the learner who wants to learn about some focus (and may not yet know what it would be useful to know) and the conceptual resources that have been developed within the society - cultural assets, so to speak. In this section, we discuss the range of tools that students might access: the different kinds of tools, and to what extent these tools can support self-directed learning. As suggested earlier, an absolute distinction between hardware and software is probably an over-simplification with some modern digital tools, but offers a useful starting point for providing an overview.

Hardware

Many digital devices (physical tools) have been made available to students working at different levels. In this chapter we discuss eReader, digital paper, smartphones, tablets and PCs as representative examples.

eReaders and Digital Paper

The eReader was one of the earliest innovations in terms of a digital educational device. One widely used example would be Kindle. Learners can read ebooks (electronic books) and view documents with it; they do not need to carry heavy books around, and they do not need to go to physical shops to buy them, or wait for those volumes to be delivered to their homes after ordering them online as they can download them (virtually) instantaneously.

eReaders also allow the user to adjust font size and colour to suit personal preferences and needs (Kuforiji & Williams, 2017), making them customisable in a way physical books are not. Such options are not simply able to respond to stylistic preferences - as such matters as typeface and colour can be important in some conditions that lead to reading difficulties, such as dyslexia (Zikl et al., 2015).

There are different models of Kindle, at different price points, with different functions: some Kindles have high pixels (that is higher resolution screens), some Kindles are waterproof, and some Kindles are specially designed for children. All Kindles have a simple and intuitive design, with the E ink screen and long battery life. The E ink display mimics the appearance of physical ink and paper and provides wider viewing angles than many light-emitting screens. Although many advanced tablets can be used as eReaders, and there are also Kindle apps designed for them, many students still prefer to use Kindles for academic purposes since no pop-ups, nor distractions from social media, will appear while studying. Learning with Kindle is self-directed as no guidance would be provided, no plan would be scheduled; it is the learner who decides what books or learning resources to read, when to read, and how long she wants to read.

Digital paper expands the functions of an eReader by providing the opportunity for users to write as they would on physical paper using digital pens. There are different sizes of digital paper (7.8", 10.3", 13.3", etc.) to cater to individual needs. They are environment-friendly as a small device may store the equivalent of a roomful of physical books, and all the learners' notes can be stored digitally. Learners do not need to worry about the loss of important pages, as they might with notes made on physical paper.

However, the writing process is (currently) not as smooth as writing on the physical paper for some grades of digital paper, and the most advanced digital paper tends to be expensive. If the digital pen is broken or lost, it is not (yet) as easy to replace as simply going into a shop to buy a pen that uses physical ink. Compatibility can be an issue as some of the digital papers require specific digital pens to access the full affordances of the digital paper. Therefore, the use of digital paper is less extensive among learners.

Smartphones

With a built-in camera and microphone, smartphones are also used by many students for their self-directed learning, especially for material they need to memorise (vocabulary, mathematical formulae, etc.). Smartphones are portable; therefore, they can be used even on the commute. It has been noted that "as young people are intensely engaging with their smartphones every day, learning occurs as it is interwoven with these mobile practices" (Chan, Walker, & Gleaves, 2015, p. 100). They can be great options for 'bite-size' learning and language learning. For example, students can record their voices to check whether their pronunciation is correct, which is useful to improve speaking skills for foreign language learners. Imagine a student needs to learn a topic from the textbook for a quiz, but she happens to recall this just before she is about to leave home for school. She perhaps spends 30 minutes on the bus, long enough for studying the material, but if the bus is always very crowded she is not able to stand on the bus with her textbook opened. So, what about the revision? She can use her smartphone to take a picture of her textbook and then take out her smartphone to study that on the bus. Many students adopt this method in out-of-class learning contexts, however, due to the relatively smaller screen size and the distractions from other apps (social media apps in particular if students do not set the notifications off whilst studying), smartphones have been less commonly used for other academic purposes (such as to watch videos, complete digital worksheets, etc.) if tablets or PCs are available. It should be noted that whilst smartphones are potentially incredibly flexible and powerful tools for learning, in some national contexts there is serious concern about what is termed 'smartphone addiction' among some young users (Bae, 2015; Haug et al., 2015). One study of middle school students in Korea suggested that something like 30% of students in this age group could be at risk of becoming 'addicted' to smartphone use (Cha & Seo, 2018).

Tablets

Tablets have been widely adopted as educational technology (Haßler, Major, & Hennessy, 2016) because of their larger screens and more advanced computing systems. Many technology leaders, including Apple, Samsung, Microsoft and Lenovo have produced tablets with different operating systems, and there are also tablets specifically developed for younger learners. As one of the products that dominate the market, the iPad has undergone many innovative developments since its launch in 2010. It is getting more powerful, flexible and, arguably, educative (Apple, 2020).

The most recent built-in technologies provide the basis for multitasking and the use of AR (augmented reality). iPad combines eReader, notebook, sketchbook, Internet browser, camera, recorder, music/video player into one portable device and offers even more learning opportunities; students can create a timetable, watch videos, write essays, fill in worksheets, and more. As many students prefer to write rather than type, some of them also use Apple Pencil for smooth, fast and accurate note-taking, sketching, and to markup documents such as study notes and teacher produced resources. iPads are used in many paperless schools due to the relatively long battery life and simple design. With the built-in affordances and guidance, there is a low barrier for teachers and students switching to instructing and studying with iPads; therefore, they can focus on teaching and learning rather than needing to commit much time to practising how to use new technology. It has been found that even with primary age learners, "the tablet PC is perceived as an easy-to-use device for educational purposes, making prior experience less decisive" (van Deursen, Ben Allouch, & Ruijter, 2016, p. 987). This contrasts with some early experiences of teachers and students adapting to new teaching technologies, given that lack of time has been described as "a universal problem" impeding the routine application of new technology in education (Al Mulhim, 2014, p. 490).

Desktop and Laptop Computers

Desktop or laptops (collectively personal computers, PCs) are also ubiquitous educational technology used by students (Gulek & Demirtas, 2005; Kumar, 2004). PCs have the largest screen sizes among the digital devices that we have been discussing; therefore, many students prefer to use them for multitasking. Students can read textbooks, handouts and supporting materials, look up unfamiliar vocabulary in the dictionary and write down notes with pens almost at the same time in the physical learning environment; whereas these tasks have to be done consecutively with most of the digital devices.

PCs were the only class of devices that supported multitasking before the latest iPadOS (operating system) was introduced. So, consider, for example, a student using her smartphone to view a PDF document (a lot of teachers prefer to convert their presentation slides into PDFs) from her science lessons, and suddenly finding some concepts confusing. She might want to note specific points so as to check with her teacher later. She would have to close the PDF viewer first and open one of the note-taking apps. If the concepts were unfamiliar, and she could not remember them immediately, she might want to switch between the PDF viewer and a search engine. However, this would be different for a PC (or the iPad with iPadOS) user. For example, imagine that a student is learning about the process of substitution in mathematics. She can first find an online lesson to watch, and if she finds some concepts challenging, then with multitasking functions, she could open a new window to search for information about the unfamiliar concepts via the search engine. She can also open note-taking software to take notes while having the video and website open. All these tasks may be directed and coordinated by students themselves; they potentially become self-teachers (autodidacts) in the digital learning context. Although learning is still being mediated culturally (a more knowledgeable other prepared the teaching video, and another more knowledgeable other produced the resource accessed via the Internet search) to provide scaffolding, students equipped with sophisticated enough metacognitive skills can effectively engage with these resources by managing the access to, selecting, and fading of scaffolding themselves.

Software

Having discussed digital devices, we now consider digital resources which can be accessed with these physical tools. Whilst it has been traditional to consider hardware and software separately, it should be noted that some devices come bundled with preloaded apps designed to allow the user to take advantage of built-in transducers (such as microphones and cameras), and the graphics technology (both high resolution screens and dedicated processing capacity). So, for example, with the iPad's built-in apps, students can edit videos, create 3D representations and sketch images - drawing upon the use of different modes to exhibit creativity.

Many educational resources can be found within apps and web-based platforms. There are hundreds of thousands of educational apps, and different kinds of web-based platforms designed for various digital devices and operating systems. Apps that fit into the 'Education' category in the Apple's App Store are grouped into many sub-categories, such as 'Learn at Home', 'Tools for Teaching', 'Learn to Code', 'Learn More with AR', 'STEM Learning for Kids', 'Train Your Brain', 'Watch & Learn', 'Buon giorno! Ni Hal! Hola!', 'Update Your Skillset', 'Explore the Night Sky' and 'Apps for Teachers' (Apple Store, accessed 14th June 2020). After reviewing some popular apps and web-based platforms, we identified the following categories based on the aims of the tools:

1) Curriculum supporting resources
2) Personal development tools
3) Artificial intelligence
4) Educational games
5) Administrative and organisational tools
6) Online meeting tools
7) e-Textbooks

Curriculum Supporting Resources

Curriculum supporting tools are especially relevant to primary and secondary school students' self-directed, but school-focused, learning. PhET, BBC Bitesize (on the website of the British Broadcasting Corporation, a public service broadcaster) and the Oak National Academy are just some examples. (We discuss PhET in more detail in the Discussion section below). The Oak National Academy is a free online platform which offers a wide range of lessons and learning materials for the core subjects, including mathematics, language, science, art, geography, history and RE. School teachers can use these resources as flipped classroom activities (see 'the paradox of flipped learning', above), or students can use them as a preparation for, or revision of, their learning. Currently, it provides learning resources for Primary (Reception, Year 1-6) and Secondary (Year 7-10) teachers, students and parents. The weekly plan is downloadable on the webpage so that students from different year groups can decide how to schedule learning in advance.

Before starting each online lesson, students are recommended to complete the introductory quiz, which helps students identify their current state of knowledge (in effect, the extent of their ZADs for the subject) and recap what they have learnt previously. Then they view a video explaining a specific topic from the syllabus provided by a teacher. The video is pre-recorded; however, there might be an interactive moment when the teacher asks students to pause the video and answer another quiz or requests students look at the slides on the next page.

Teachers in classrooms use techniques, or 'moves', such as these to help engage students with key ideas in learning material, and in particular to help them link new learning to more familiar material (Taber, 2018b). This process is always (if not always deliberately) informed by the teacher's mental model of the student's current level of knowledge and understanding, which enables the teacher to judge how to best work in a learner's ZPD. Even when teachers know classes well, and have undertaken diagnostic assessment to, for example, check on prerequisite learning, the teacher's mental models of the students' knowledge and understanding is inevitably partial and imprecise. In a face-to-face teaching situation the teacher asks questions and sets activities during the lesson that (even if the teacher does not think in these terms) allows them to test and judge, and so update, their mental model (Taber, 2014). Clearly, a teacher offering a video lesson to students they have never met is only able to operate with a very generalised mental model of the students they are supporting.

After viewing the video, there would be a recap quiz, helping students assess their progress in learning. After submitting their answers, students can view the accuracy report which also informs them of the correct answers. If students found any of the questions challenging, they could watch the lesson again or repeat the previous exercise. Our comments, above, about student metacognitive sophistication are highly relevant here. If the quizzes are well designed, then any student who successfully completes them can recognise that success. A student who gets some answers wrong, and cannot appreciate the basis of the correct answers (that is, rather than simply try to learn them by rote for the future), however, cannot ask for further clarification as they might in a classroom. That is a limitation when the app is seen as a stand-alone resource, but of course does not undermine its value for a learner who *also* has access to a teacher and is using the digital resource to supplement classroom learning.

After completion, students have opportunities to watch other lessons from the same topic or complete the next lesson in the same series. Students may skip any of these steps according to their learning habits (and again, metacognitive sophistication will support effective judgements in this regard). Detailed instructions on the activities, and what the students need to do if they want to rewatch or skip the videos, are provided.

The Oak National Academy was recently established in the context of the COVID-19 pandemic we referred to earlier, and in association with the UK government's Department for Education in England, to meet the needs of students studying the National Curriculum for England whilst 'home schooling'. Given the emergency (with most school pupils being excluded from schools due to public health considerations) it was brought into the public domain very quickly, despite pedagogical and technical limitations. For example, although students are invited to undertake a quiz at the start of a lesson, which could usefully focus their minds on relevant prerequisite knowledge, perhaps acting as a scaffolding 'PLaNK' (see the Discussion section below) or advance organiser (Taber, 2018d), the subsequent video viewed is the same regardless of their attainment on the introductory quiz. While learners come to the virtual class with different extents of ZAD, and with different potentials to work in their ZPD, the lesson content is the same, which could be too demanding for some of the learners while lacking challenge for others.

Another technical limitation is that the lesson video and slides are not on the same page; learners need to pause the video and turn to the next page to access the slides. However, given that the Oak National Academy has been established within a relatively short amount of time, these aspects could be considered teething problems or bugs to be 'ironed out'; the limitations may be overcome as the platform is developed. The website informs teachers that the "classroom resources in no way replace the crucial teacher to student relationship. They're a means of supporting and complementing your own work at this difficult time."[3] This is a recognition, then, that, as suggested above, on-line resources often lack the interactivity of face-to-face teaching which Vygotsky's model of development suggests is so important for learning that goes beyond 'drill and practice' intended to consolidate prior learning, or straightforward assimilation of additional details and examples within existing, well-established frameworks/schemata.

There are other tools including MOOCs (see above), edX, Coursera, Kahn Academy (see above), Future Learn and Udemy etcetera. Learners can find courses that they are interested in across different platforms. The pattern of these online courses used to be limited to a number of taught sessions with homework; students watch videos of each session and they have the freedom to drop out the course at any time. With the development of Web 2.0, more interactive features have been added to MOOCs and other similar platforms, including built-in quizzes during the session, and forums for discussion, as well as the sharing of learning material. However, they may not be primarily designed according to the curriculum for any particular students; indeed,

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[3] https://www.thenational.academy/information-for-teachers# accessed 1st June 2020.

learners can access many online courses from different domains and institutions around the world. These online resources can be used to complement learners' school lessons or university lectures, or they may be used to explore learners' personal interests in informal learning. As we highlighted above, such resources may be very valuable, but this may depend upon the metacognitive skills of those using them as they direct their own learning.

Personal Development Tools

There are tools designed to support personal development. For example, Elevate is a popular app designed for 'brain training' to improve cognitive skills (internal tools). The website claims that "across four key skill groups, Elevate users enhanced their performance by 69% compared to non-user"[4]. The report on which this is based is available on the company website (Nakano & unamed others, 2015) and claims that "the Elevate treatment group, which had access to Elevate games and training exercises, scored higher and improved more than the control group, which did not have access to the games and exercises" (p.1).

This appears to be an otherwise unpublished report that does not seem to have been subject to any form of peer review. Dr. Dana Nakano is cited as the 'principal author' and "was an independent analyst for the project, which was carried out under the direction of the Elevate educational content team with the assistance of Nichols Research, Inc.", but the other researchers are not named, contrary to normal academic practices (Taber, 2018a). The design of this research is inadequate. In any such 'experimental' study, the assignment to the experimental group (receiving the treatment of interest) and control groups should be random, so that each participant has an equal chance of being in either condition (Taber, 2019). However, this study selected the experimental group from people who had *already chosen* to register with the site and thus were motivated to improve on the target skills,

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[4] https://www.elevateapp.com/research accessed 17th June 2020.

whilst the ‘control’ group (actually a comparison group - as there were no strict controls) were recruited and paid to take the pre- and post-tests based on a range of broad characteristics applied to both groups “reside in the United States, be fluent in English, own a smart device, be 18 years of age or older, and possess at least a high school diploma and no degree greater than a master’s” (p.1). Not surprisingly, the experimental group performed significantly better on the post-test than the comparison group - but they also performed significantly better at the start of the study: “In the pre-test, the Elevate group scored 40% higher than the control group. For the post-test, the Elevate group scored 45% higher than the control group” (p.3).

The study does not offer any examples of the test items or the development activities, so readers are left to speculate as to what extent the increased performance on the post-test reflects general skill development rather than just familiarity with a type of item. Given that simply undertaking the pre-test seemed to allow the comparison group to do 40% better on the post-test (if it is accepted, as claimed, that these tests were equivalent, as how this was ensured or verified is not reported), this is a major limitation. This is especially relevant given our distinction, above, between the kind of learning which is just about refining accuracy and speed with existing skills, and the kind of learning which might be considered *development* in Vygotsky’s terms.

There are also tools with more specific foci. As one example, Duolingo provides short lessons, games and quizzes for language learning. These can support formal learning, but also offer engaging activities for the self-directed learner. It is claimed on Duolingo’s website [5] that “with more than 300 million learners, Duolingo has the world’s largest collection of language-learning data at its fingertips”. It is reported that a number of experts in “AI and machine learning, data science, learning sciences, UX research, linguistics, and pyschometrics” work with Duolingo, and Duolingo has also supported a number of research studies relevant to linguistics and machine learning (Markant, Settles, & Gureckis, 2016; Römer & Berger, 2019; Streeter, 2015).

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[5] https://research.duolingo.com, accessed 17th June 2020.

The language learning on Duolingo often involves quizzes asking students to choose the right translation of a phrase or a sentence; this would be helpful for improving communication skills, however, if the learner choses the wrong answer, the correct answer is displayed without further explanation, and there is rarely any explication of the grammar or how to construct a sentence in a foreign language. Many languages are taught in terms of a range of topics on Duolingo, which makes it easy and practical, especially for beginners. All learners need to complete introductory quizzes when they sign up for a new language; this helps Duolingo identify (in effect) features of the individual learner's ZAD, so that learners can start from the most appropriate levels. However, as the topics are not arranged accordingly, it may still be hard for some learners to select those options that will best scaffold their learning since the chosen topic might be too easy (within the ZAD) or too difficult (in the ZDD) for them.

Artificial Intelligence

Many AI (artificial intelligence) approaches and systems have shown their potential for supporting various forms of educational activity (Tuomi, 2018). Increasingly, curricular supporting tools and personal development tools have built-in affordance to act as a teacher offering feedback thanks to AI technology. This may compensate for the physical absence of a teacher. For example, a mathematics learner's calculations can be assessed and corrected, after simply taking a photograph with the device's built-in camera; a language learner's speaking can be judged and improved with the input through the built-in microphone. The digital devices, including smartphones, tablets and PCs are starting to "talk" and interact with the learner.

There are AI assistants which help with enhancing individualised learning experiences. For example, Amazon Alexa, Siri and Cortana can help students arrange administrative plans such as scheduling; these AI assistants can also answer common and simple questions. With the Presentation Translator plug-in, PowerPoint users can access real time subtitles for lectures being taught in another language. Although there are debates regarding the privacy issues raised by the data collection that occurs during machine learning or AI, these functions have helped learners achieve many outcomes that we may not have imagined a few years ago. Marr (2018, 2) has argued that "since the students today will need to work in a future where AI is the reality, it's important that our educational institutions expose students to and use the technology."

The increasing use of 'chat-bots' as the first level of customer-support on many websites may give the impression that such technology is far from having genuine intelligence - when many queries are met with requests to rephrase the questions or completely irrelevant responses. However, machine learning relies on training systems with extensive data, and in some other areas such technology has been demonstrated to become incredibly powerful - so, as one example in the area of medical diagnosis, automatic systems for analysing radiography scans are now considered to be as accurate as experienced diagnosticians - whilst being able to assess scans very much faster (Jiang et al., 2017; Miller & Brown, 2018). That is, of course, an area where the critical nature of the work (literally, a matter of life and death for patients) has justified the commitment of a high level of resource to research and development, but this does suggest what is possible for educational tools. The history of information technology also suggests that what is expensive and exceptional at one moment can often become affordable and widespread in a matter of a few decades. Although it seems that "education might be somewhat slower in adopting artificial intelligence and machine learning", there are AI mentors and more AI learning apps being developed, and more opportunities will be offered to students, parents and teachers in the future (Marr, 2018, 7).

Educational Games

It could be argued that many curriculum supporting tools have the element of gaming to motivate learners (e.g., PhET, see the Discussion section below); and indeed it has been suggested that there is no clear distinction between games and educational simulations (Podolefsky, 2012). Curricular supporting tools often have sequenced video lessons and the learning materials are grouped into topics, whereas educational games may not be primarily designed with any specific curriculum material in mind. One educational game can only focus on one topic, yet they can often help learners understand abstract concepts with hands-on experiences. Many games use AR/VR (augmented reality/virtual reality) technologies (Vidal, Ty, Caluya, & Rodrigo, 2019) and this makes them extremely attractive to many players. The solar system is a popular topic for AR games since students can “touch” and “twist” planets which clearly cannot be achieved in real life. Students may construct new understandings regarding aspects of the solar system after playing with such games; however, it is also possible that students may not learn anything significant due to the pedagogical perspective not being an imperative for the game designers (cf. Laine, 2018).

Many games are made for profit, and although more people might download the free games, the paid games and the games with in-app purchase are usually equipped with more functionality and better affordances. This is understandable since significant investment is needed to attract and resource well-experienced designers and developers; and users expect more when paying for an app. Although education is not the most dominant game genre in the market, the AR, VR and AI technologies have provided scope and opportunities for high-quality educational games with built-in affordances; and more research could usefully support collaboration between educational researchers/practitioners and the tool developers so that learners can access more educational, whilst entertaining, games in the future.

Administrative and Organisational Tools

There are learning management systems (LMS), note-taking tools (Notes, Notability), schedule arrangement tools (Calendar) and checklist tools (Reminders) available on the market, and indeed often bundled with devices (so Apple devices often have a suite of productivity tools installed with the operating system). These tools can help learners improve their personal productivity. An LMS is a web-based platform or app that can manage students' learning progress (Gorshenin, 2018) - an alternative term often used for similar systems, such as Moodle (Modular Object-Oriented Dynamic Learning Environment) for example (Parsons, 2017), is virtual learning environment (VLE).

An LMS can be a versatile assistant that helps teachers take charge of all the digital devices used in the classroom. Tools including Google Classroom and Schoolwork developed by Apple are representative examples. These apps provide platforms for sharing learning materials, handouts and homework. They also provide an opportunity for communicating between teachers and students, from anywhere, at any time. More importantly, students' learning progress can be tracked by teachers - or students' parents - even if they are physically distant from each other. These tools are also all-in-one-place; learners do not need to worry about losing teaching handouts or important notes for revision. These types of systems can be used simply as a paperless alternative to traditional teaching materials: handouts, student notebooks handed in for marking, teacher mark-books, etcetera. However, they often offer considerable additional functionality.

As just one example of a possible activity (used by one of the authors), a class can collectively compile a glossary of terms for a topic - by working collaboratively in real time using a VLE. They can do this in the same classroom, or from diverse locations. Students (and a teacher) can see, edit, and build upon each other's contributions. This can be considered to be a suitable type of learning activity from the viewpoint of constructionism (Papert & Harel, 1991) - where people work together to learn through building an artefact. VLEs offer a wide range of tools that allow live chat, learner diaries, and much more. From a Vygotskian perspective it is not the paperless nature of such tools that is most significant, nor even the possibility of different learners being remote at different locations, but the opportunities for interaction and personalisation that allow shared activity of a kind that supports scaffolding of learning within learners' ZPDs.

Online Meeting Tools

As we stride into a new era of remote education, a shift that was accelerated very abruptly by the need to respond urgently to the COVID-19 pandemic, lessons, supervisions (tutorials) and meetings can be carried out remotely, which should be a catalyst for the further development of online meeting tools. Zoom, Tencent Meeting (VooV Meeting) and DingTalk are examples of the most commonly used online meeting tools. These tools allow attendees to join meetings via smartphones, tablets and PCs. One-to-one supervisions and larger-scale lectures can be delivered through these tools smoothly, lively and interactively. This does of course assume that those involved not only have the devices, but also ready access to reliable and fast Internet connections. This may be something that it is reasonable to assume in some national contexts, but globally the infrastructure is not in place for all learners.

Real-time screen sharing and opportunities for collaboration make the online meeting even more convenient. With these tools, teachers do not need to record lessons for students; they can arrange live lessons with students which do not require time for pre-recording and editing. Individualised one-to-one lessons can be carried out with these tools, but even whole-class teaching can be more effective at scaffolding students' learning than pre-recorded videos, as such tools can, in principle, support the kinds of interactivity that turns lessons from being just lecturing, to teaching that collects feedback in real-time and so supports work in learners' ZPDs - in the ways suggested earlier in the chapter.

However, the risk of potential distractions noted earlier regarding smartphones can be an issue. There could be a number of pop-ups being pushed during the online lesson or meeting, and there are attractions from other entertaining and social media apps installed on the same device that students use to attend the online meeting, exacerbating some students' limited attention spans. It can be hard for remote teachers to judge whether students are typing for note-taking purposes or chatting with friends. (Those who have attended meetings by video will likely have heard the sounds of typing picked up by other participant's microphones during a discussion and wondered what was being typed - but then when actually meeting together for paperless meetings colleagues do not know if others across the table are looking at the meeting papers on their screens, following-up on a point raised by checking the Internet or other resources, making notes as memoranda, or actually engaged in some activity unrelated to the meeting.)

As a result, some parents may feel that they have to attend the lessons with the young learners to make sure that they are paying attention to the lessons (or at least they are staring at the screen without engaging with other apps). In order to reduce demands on parents, and to create suitable environments for learners to remain focused, technical improvements might need to be considered by the online meeting software and platform designers and developers. For example, Apple devices offer the ‘Do Not Disturb’ function, which will silence calls and notifications when turned on, which could help young learners keep focused to some extent. Would it be acceptable in a virtual classroom context for the teacher to be able to monitor which apps the students had open on their devices, when this might be considered an inappropriate invasion of privacy in other contexts?

eTextbooks

Increasingly hard copy textbooks are being replaced or augmented by “smaller study guides, chapter summaries, flashcards, as well as short smart notes” (Schmelzer, 2020, para.4). In a similar way, eTextbooks (electronic textbooks) can go beyond just being paperless books read on eReaders, as they can provide a degree of interactivity not possible with traditional books (Jesse, 2014). In some subject areas (literature for example), students may be encouraged to annotate schoolbooks, but more commonly learners are told they cannot mark school-owned books issued as textbooks, as these often need to be collected at the end of the course so they can be reissued to later cohorts of students.

Yet eTextbooks are accessed as file copies which allow individualised highlighting and note-making. Moreover, they can be shared. So, teachers can add notes to a book used with their classes to customise the book for their course and their students, and then issue the annotated book to their classes. Moreover, students can make their own annotations, including on points where they are unsure or have questions. These annotations can be shared with the teacher - thus they allow a conversation where the teacher can read, and respond to, the students' questions and comments (Nourie, 2019).

So rather than every reader of the same textbook having an identical resource, each teacher can issue a customised version (or indeed multiple customised versions for different groups of students), and then each student's copy can be further personalised over time with teacher input directly targeted according to the specific responses of the individual learners to the text. In this way an eTexbook affords a dialectical process of the type that Vygotsky associated with development. Unlike a traditional text, therefore, there is much more potential to use the text as a tool for working in different students' ZPDs.

DISCUSSION

Having very briefly offered an overview the range of digital tools available to learners, we now wish to consider the extent to which these tools can support the kind of scaffolding that Vygotsky thought was so important to learner development. Given the range of tools available, this discussion will largely be in general terms, but will draw upon two examples of resources intended to support independent learning in the sciences. We will also offer a metaphor for scaffolding - also from the natural sciences.

Characteristics of Learning Scaffolds

One of us has suggested that there are certain criteria for scaffolds:

1) They must ask the learner to undertake an activity/task which is beyond their present ability if unsupported;

> 2) They must provide a framework of support within which the learner can be successful by relying on the structured support;
> 3) They must provide reduced support as the learner becomes familiar with the area, and is able to cope with increased demands; and
> 4) They must result in the learner being able to undertake (unsupported) the activity/task which was previously beyond them. (Taber, 2002, p. 74)

Taber proposed two types of scaffolding tools: PLANKs and POLES. PLANKs are "PLAtforms for New Knowledge" and POLES refers to "Provided Outlines LEnding Support" (2002: 74). Scaffolding PLANKs direct the learner's focus onto the specific prior learning relevant to the new task and may seek to organise it in the best way for it to act as a foundation for the new learning. Scaffolding POLES structure the learning activity to guide the learner towards the target learning, modelling for the learner what they will come to achieve unaided once the scaffold is removed.

In classrooms, teachers can use digital technology as tools to present teaching materials, organise scaffolding activities and help students construct new knowledge. However, in out-of-class contexts, students have to build up new ideas and construct the outline for the new knowledge by themselves. For digital technology to be effectively used for students to learn science in out-of-class contexts, the nexus of software and hardware tools employed in a learning activity have to be equipped with scaffolding potential so that the learner can effectively work in his or her ZPD.

Scaffolding Learning as Akin to Enzymatic Catalysis

Metaphors and analogies should always be considered critically, as the aspects that do not map onto the target they are being used to illustrate can often be as salient and as relevant as the aspects that map positively. Given that, and in the spirit of offering a way to imagine scaffolding (rather than an objective description) we suggest it may be useful to think of scaffolding learning as like the enzymatic catalysis of a chemical process in the body (see Figure 3).

Some chemical reactions are energetically viable (in chemical terms, exothermic) and so in thermodynamic terms, occur spontaneously. However, sometimes even theoretically viable (so spontaneous) reactions occur at such a slow rate that for all practical purposes there is no reaction. For example, imagine a wooden dining table in a room at 293 K (20˚C) with an atmosphere containing about 21% oxygen - a situation found in many people's homes. The combustion of the table is a viable chemical process [6] and indeed the wood will (theoretically) spontaneously burn in the air. Yet, of course, that does not actually happen. Despite being a thermodynamically viable process, the rate is so slow that an observer would die of old age long before seeing the table burst into flames, unless some external agent actively initiated the process. If parents returned home from an evening out to be told by their teenage children that the smouldering dining table caught alight spontaneously, the parents would be advised to suspect that actually this was not strictly true. Although the process would be energetically favourable, there is a large energy barrier to its initiation (cf. Figure 3, top image). Should sufficient energy be provided to ignite the table, then it is likely to *continue* to burn vigorously, but without such 'initiation energy' it would be inert.

The process of catalysis allows reactions which are energetically favourable, but which would normally occur at a slow or even negligible (and in the case of our wooden table, effectively zero) rate to occur much more quickly - by offering a new reaction pathway that has a much lower energy barrier (such that this is more readily breached by the normal distribution of particles at the ambient temperature).

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[6] We avoid the term 'reaction' here, as strictly a chemical reaction occurs between specific substances. Wood is a material composed of a wide range of different compounds, and so the combustion of wood is a process encompassing a medley of concurrent reactions.

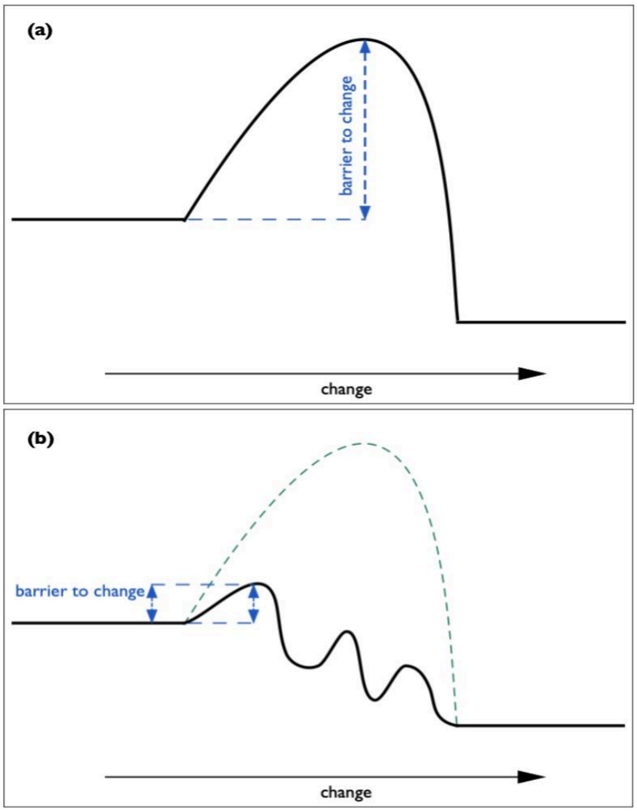

Figure 3. Scaffolding learning can be seen as analogous to enzymatic catalysis (b) which facilitates a reaction with a substantive energy barrier (a).

In living organisms, a class of catalysts known as enzymes, catalyse reactions. Enzymes tend to be specific to particular reactions and very effective catalysts, so reactions akin to the burning of organic materials (as found in our wooden table) can occur as part of metabolism at body temperature. The second image in Figure 3 represents shows the same chemical reaction as in the top image (note the same start and finish points) reflecting how an enzyme changes the reaction pathway, but not the overall reaction. Two particular features of this graphical metaphor are that the overall process is broken down into a number of discrete steps, and the 'initiation energy' needed to get the process underway is very much smaller.

This is similar to the mediation of learning trough scaffolding, where a task that is currently beyond the capacity of the learner is broken down into a sequence of smaller steps, more manageable 'learning quanta', and the learner is guided along a learning pathway. The parallels go beyond this. Part of the way that an enzyme functions is that the enzyme molecule's shape is extremely well matched to bind to a target reactant molecule (something reflected in the teaching analogy of the 'lock and key' mechanism of enzymatic action: the enzyme and substrate molecules are said to fit together like a lock and key). This is analogous to how effective scaffolding requires a teacher to design a scaffold that fits the learner's current level of development: that is, her current thinking and skills. Once the substrate molecule is bound to the enzyme molecule, this then triggers a specific reconfiguration: just as a good scaffolding tool suggests to the learner a particular perspective on the subject matter.

Moreover, whereas a free substrate molecule could potentially follow a good many different pathways, once it is bound to the enzyme molecule its 'degrees of freedom' are reduced, so there are then significant constraints on which potential changes are still viable. Most organic chemistry carried out in vitro (in laboratory glassware) is inefficient as there are often many 'side reactions' that lead to unintended products, just as students may readily take away very different interpretations from the same teaching, so the yield of desired product can be low. However in vivo reactions (in living cells), being enzyme-catalysed, tend to give high yields.

The process of enzymatic catalysis therefore makes the preferred pathway much 'easier', offers a guide along the intended route, and channels change to rule out alternative pathways. Digital tools that support teaching to meet curricular aims, such as apps intended to be used by learners to support study, therefore need to offer similar affordances (structuring student learning) and constraints (reducing the degrees of freedom to go 'off track'). Clearly this will rely on design features built into the tool. Here we very briefly discuss two examples.

An Example of a Tool Offering Explicit Scaffolding

It has been argued that an application designed to support independent study that can facilitate the more substantive category of learning ('accommodation', or development in Vygotsky's terms) has to encompass an instructional model, and so

> needs to be a lot more than a textbook transferred to a computer, but ideally will provide at least the following features:
>
> - providing the learner with an overview of the area to be covered near the start;
> - providing navigation options to allow the learner to move about the material according to their own needs;
> - offering questions with feedback for the learner to check their understanding;
> - 'scaffolding' to allow learners to build up their understanding at their own pace…[which means that] the instructional design has to help the student recognise which prerequisite knowledge is relevant, and show them how it fits with new knowledge – as well as offer a way of structuring prior learning with new information to build up new understandings. (Taber, 2010b, pp. 44-45)

One of us has previously described an example of how National Learning Network (NLN) materials, produced to support physics learning in further education colleges in England, were developed in accordance with a pedagogic model giving a set of discrete teaching/learning units where:

> Each unit began with an introductory screen that was designed to engage the learner's interest and introduce the topic covered…Next comes a screen concerning the aims of the unit, setting out what the student should expect to learn when completing the unit. This is followed by a screen eliciting 'first thoughts' - where a student is asked a question to get them to think about their existing understanding of the topic area…The next screen or two make a 'presentation' of the main ideas being explored in the unit. This usually involves some form of interactive animation…There

> then follow a number (c.5) of 'investigation' screens, which allow the learner to explore the key idea in more detail…After working through the 'presentation' and 'investigation' sections offering the core knowledge, the learner is invited to apply their knowledge by answering an open question that tests understanding of the learning objectives built into the unit. A model answer is provided that the student can compare against his or her own response. This is followed by a 'summary' which highlights the key learning points, and then a 'check your understanding' section of three screens offering objective questions (where the student responses can be logged for a tutor). (Taber, 2010b, pp. 47-48)

This example includes some of the features which we have considered characteristic of good teaching - attempts are made to engage with students' interests and to highlight prerequisite knowledge, and there is an activity which simulates some kind of practice where the learner's actions produce simulated outcomes that give feedback on those actions (a kind of structured enquiry activity), and there are opportunities to apply and test learning with some feedback on performance. This is clearly much more than simply being provided with information, as rather it is designed more like a teacher's lesson with its shifts in activity. Instructions, suggestions, information provided, questions asked, feedback given, all reflect the moves a teacher will make during teaching (Taber, 2018b). There is clear scaffolding in terms of how specific prerequisite knowledge is activated, and questions and activities are designed to lead the learner through a specific 'thinking pathway' (Taber, 2018d). For example, the simulations offer a limited number of potential moves for the learner - a small number of actions to undertake or variables to change (so restricting the 'degrees of freedom' that would be found in a real practical context where students may deliberately or inadvertently be engaging with apparatus and materials in ways irrelevant to the intended learning goals).

That said, the degree of interactivity in such a tool is still limited. The feedback and hints are designed to offer responses to common variations in student thinking patterns (as may be predicted from the research on student alternative conceptions), but if a student reaches some unanticipated idiosyncratic interpretation, as can often happen (Taber, 1995), there will be no contingency. In such a situation, a teacher could spot the issue, and compose a specific response for that student in the moment (which is not to say this will always happen, of course) - which the app cannot do.

This specific example was intended for 16-19-year-olds who, by the nature of taking elective physics college courses, were likely to be above average for their age cohort in terms of their academic performance. This group of learners will therefore be expected to have well developed metacognitive skills which will support them in using the tool effectively. So, whilst this particular example of digital tool certainly falls short of the support of a skilful teacher directly interacting with the student, the combination of designed features and target group (see Figure 1) still makes it a useful learning tool to support teaching, with potential to scaffold learning when used in private study by a learner. We have described this as an example of *explicit* scaffolding as it involves the embedding of a simulation within a programmed teaching sequence with explicit learning objectives that are shared with the learner.

An Example of a Tool Offering Implicit Scaffolding

Whilst the tools just described proved useful with some younger (14-15 years of age) learners (Taber, 2010b), they were not designed for use with the general school population. The resource base of widely used PhET simulations (or 'sims') referred to earlier in this chapter was also initially intended for use in college teaching, but has been extended to offer sims that can be used with school age learners (Podolefsky et al., 2013). Podolefsky and colleagues describe how the PhET team developed a model for building into simulations what they describe as 'implicit scaffolding':

> In the framework for implicit scaffolding, scaffolding is built into the tool itself – using affordances, constraints, cueing and feedback – in such a way that students find productive inquiry paths and are supported in their learning without requiring explicit instructions…By incorporating implicit scaffolding, the learning environment or tool (e.g., a sim) can support

> students to learn and move into their ZPD with minimal explicit guidance from a teacher or worksheet. Furthermore, implicit scaffolding can provide an inherent flexibility that can support students along varied, individualized learning trajectories, fulfilling the need for adaptability in scaffolding. (Podolefsky et al., 2013, pp. 2-3)

This quotation reflects many of the points we have been making in this chapter, and the PhET initiative is perhaps the best example that we have come across of the development of digital tools to support the kind of learning (i.e., beyond assimilation) that could be considered *development* in Vygotsky's terms. A key aim in the PhET programme is to help students "take ownership of the learning experience [so that] students perceive a sense of agency, where they can direct their own scientific exploration" (Podolefsky et al., 2013, p. 4). Thus, there is a stronger element of enquiry learning than in the NLN modules discussed above, as PhET deliberately provides a lower level of explicit guidance for learners in terms of what they are meant to do during enquiry (Riga, Winterbottom, Harris, & Newby, 2017). Where the NLN materials suggest what to 'manipulate' and change, and what to observe, the PhET materials offer more of a sense of free exploration. 'A sense of…' as the design of the simulations subtly restricts the actual degrees of freedom available through constraints, and focuses attention on specific features. The constraints "restrict actions [and] are productive when the limitations they place increase the likelihood of intended usage" (Podolefsky et al., 2013, p. 6) - thus the channeling along a particular path of activity is stronger than it may appear to the learner, as the scaffolding is designed to be implicit,

> Implicit scaffolding is meant to allow for student autonomy, the feeling that students have independent control over their experience, while both affording and constraining students to actions that are productive for learning. Students perceive the sims as engaging, open exploration spaces. Yet, the implicit scaffolding provides cuing and guidance so students are inclined to interact with the sims in productive ways; it guides without students feeling guided. (Paul, Podolefsky, & Perkins, 2013, p. 3012)

The PhET team have developed an extensive model/protocol for developing their simulations according to their principle of implicit scaffolding (Podolefsky et al., 2013) - for example, limiting the use of text, and incorporating visual cues. These include using tactics such as familiar iconography, proximity between elements, colour, etc., to tacitly direct – 'nudge' - user attention.

Both the NLN materials and the PhET simulations go well beyond being simply sources of information, to offer interactivity of the kind students meet when working with teachers, and having built-in means of offering feedback. The different styles reflect somewhat different curriculum aims, with the NLN materials developed in a curriculum context that puts a higher premium on the learning of subject matter (Taber, 2018c), and the PhET simulations (used globally, but deriving from the United States context) seeking to offer a stronger flavour of learning by enquiry (Lawson, 2010).

CONCLUSION

We would consider these two examples of digital tools to go some way towards offering the kind of scaffolding that allows a learner to vicariously experience that which they are not yet ready to master - something that is not generally achieved simply by reading a textbook or listening to straightforward lecture presentation. Yet, it is clear that even when such materials are designed with specific educational objectives in mind, and extensively developed and refined according to a pedagogical model, they can only go so far to replacing a subject expert who is present to interact with the learner (Taber, 2010b). This is clearly recognised by the PhET developers who note that

> We do not aim to minimize the teacher's role, nor do we intend for the implicit scaffolding to be the only scaffolding. Rather, by offloading some of the scaffolding responsibilities onto the learning environment or tool, the teacher then has more flexibility to adapt their role in the classroom to meet students' needs. (Podolefsky et al., 2013, p. 4)

It seems clear that there are now a wide range of digital tools that have potential to support both formal and informal learning. Some are little more than quicker and more convenient versions of existing analogue tools. However, increasingly, more sophisticated tools are becoming available that are more interactive, intuitive, and customisable.

For the self-directed autodidact, the digital revolution has offered very powerful learning tools. For the classroom teacher with the knowledge and skills to potentially scaffold learning by working in the ZPD of each student in the class, there are now very useful tools that can support that process and make it more viable when working with large classes. When learners are required to be at a distance from their teachers (in distance learning courses - or indeed during a pandemic) there are now many tools that can be employed which offer more engagement and interactivity to replace assigning a textbook.

There has clearly been much progress in recent years. At the moment it is generally the case that for the typical young school-age learner these advances still fall well short of being able to replace (rather than supplement or augment) working with a teacher: but given the progress in sophistication and integration of tools in recent decades, and examples of what can be achieved when resources and educational expertise are concentrated into tool design and development (and justified by ensuring those tools then have global reach) perhaps a revolution in the nature of schooling - accelerated by experience during response to the COVID-19 pandemic - may be possible. Likely, it will always be desirable to have schools where students can meet with each other and with teachers, at least some of the time - but perhaps when high quality, interactive, learning resources are widely available across the curriculum, the teachers will be able to focus more on working in each learner's particular ZPD, drawing from a repertoire of tools that than can be personalised to function as suitable and fadable scaffolds for specific learners.

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