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A study to explore the potential of designing teaching activities to scaffold learning: understanding circular motion

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Abstract

Scaffolding allows a learner to succeed in tasks beyond their current developmental level, through sharing in activities that can facilitate the learner to internalise that activity through social mediation. This guides the learner's development towards autonomous success in the activity. The process is effective to the extent that the shared activity supports the learner in meaningfully engaging in, and eventually mastering, the activity. The notion of scaffolding was introduced in the context of a single child being supported by an adult who is giving them their full attention - where teaching, and so learning, can occur implicitly within the context of everyday interactions such as play. Extending the principle of scaffolding to the planning of teaching and the design of learning activities in formal whole-class contexts is challenging. The present paper reports one small scale study that explored an attempt to design materials using principles of scaffolding in an aspect of upper secondary physics known to present learning difficulties to students. An activity to potentially scaffold new conceptual understanding (a scaffolding POLE) was prepared to be undertaken after a short activity to reactivate prerequisite learning (a scaffolding PLANK). The materials were administered to students (n=122, c.16-17 years of age) taking an elective upper secondary (high school) physics course. The results demonstrate the difficulty of estimating the level at which to pitch learning materials intended to scaffold learning, but also suggest that such materials may contribute to shifting student thinking even when they are not optimally 'tuned'. The results of this small scale study indicate both the difficulty and the potential of transferring the scaffolding principle from dyadic (e.g., parent-child or tutor-single student) contexts to formal classroom teaching.

Introduction

Scaffolding is a term widely used in discourse about pedagogy, but is sometimes intended to mean little more than supporting learning or structuring learning activities. However, the notion of scaffolding was proposed (Wood, 1988; Wood, Bruner, & Ross, 1976) in a particular theoretical context drawing on the developmental theories of Vygotsky (1934/1986, 1978). Scaffolding allows a learner to succeed in tasks beyond their current developmental level, through shared activity with another or others that can facilitate the learner to internalise the socially mediated activity. This learning process can guide development (Taber, this volume). The process is effective to the extent that the shared activity supports the learner in meaningfully engaging in, and in time mastering, the activity. This implies that the nature of the learning activity, and the type of support offered, has to be judged carefully - to extend the learner, but pitching the task demand to ensure it is accessible to the learner with the level of support offered. This is the challenge of constructing scaffolds in teaching.

Within the terminology used in Vygotsky's (1934/1986) perspective, scaffolding has to occur within a kind of 'activity space' known as the zone of proximal development (often just referred to as the ZPD), because the potential for supported activity to facilitate substantive learning is considered to be limited to activities that, in terms of the spatial metaphor, are relatively near to the zone within which a learner has autonomous competence, which is referred to as the zone of actual development or ZAD (see Taber, this volume).

Initially the idea of scaffolding was applied to situations where a learner engages in an activity with a parent, teacher, or more advanced peer (Wood et al., 1976). In such dyadic contexts, the 'teacher' has one learner to focus on, and so can given them all their attention, whist being primed to notice signs of whether a learner is struggling or succeeding. That is the person taking the teacher role will likely be aware whether the learner is fully engaged, or is frustrated (if more support is needed), or is bored (if there is insufficient challenge). In such a context shared activity can be direct and extensive, and provides the 'teacher' with ongoing feedback that allows them to modify the level and type of support when indicated.

Whilst the principle of scaffolding learning is commonly seen as important in classroom teaching, this is clearly a more challenging context than in dyads as (a) learners within the class will inevitably be diverse in relation to their current stages of development, with different levels of skills, knowledge, and so forth, and so will have different potentials to make progress; (b) the teacher's attention to each individual learner, necessary to notice cues that act as feedback indicating that a task or the level of support should be modified, is limited in the whole class situation. Given the perceived value of the notion of scaffolding, there is then a major question regarding the extent to which the principle can be applied in school teaching, and a challenge to offer teachers feasible tools to help them apply the principle of scaffolding in the planning of teaching and the design of learning activities in formal whole-class contexts. Scaffolding may apply to learning complex skills (e.g., learning how to correctly focus an optical microscope), mastering multistage processes (e.g., using back-titration to calculate an unknown in the chemistry laboratory), or developing conceptual understanding (e.g., such as mastering the theory of natural selection).

In the present study we are primarily focused on the latter type of classroom learning, drawing on an example from school physics. The present paper reports one small scale study that explored an attempt to design materials using principles of scaffolding in an aspect of upper secondary ('high') school physics known to present learning difficulties to students. The study drew upon two distinct types of scaffolding tool that are considered to have different roles in supporting learning (as discussed below).

Classroom teaching often involves introducing conceptual material that is new to students, but builds upon existing learning (Taber, 2011). Effective learning of new concepts, theories, perspectives, models, etc., often depends upon students engaging specific pre-requisite learning (Taber, 2015). That is, the conditions for what has been called meaningful learning (Ausubel, 2000) include both that the learner has available within their cognitive structure material that is potentially relatable to what they are being asked to learn; and further that they recognise this relevance, and so bring the expected prior learning to mind. Even then, students may have alternative conceptions (Gilbert & Watts, 1983) of the prerequisite topics that (from the perspective of the target knowledge presented in the curriculum) misdirect the new learning; or a student may make unhelpful links with (from the teacher's perspective) the 'wrong' prior learning, and so misinterpret teaching (Taber, 2001).

Vygotsky's perspective focused on the role of tools in learning. A critical tool is a shared language (Vygotsky, 1934/1986), but various other symbolic systems and tools are also available within, and acquired from, the culture (Vygotsky, 1978). These can take various forms. So the formalisms of pie charts, line graphs, and Venn diagrams, can be considered as such tools. So can a dictionary, the periodic table, an ordinance survey map, and the emoticons sometimes used to complement text to indicate whether a statement is made in anger, sadness, triumph, or jest. Even something as taken-for-granted as the use of syllogism [1] can be considered a thinking tool acquired from culture (Luria, 1976). Engaging with such tools in shared activity can lead to them being internalised so that they are available to support an individual's thinking and further learning and development.

Teaching materials prepared by teachers and curriculum developers can also be considered to be tools in this sense. Attempts to design materials to scaffold learning in school classes often focus on the development of the new learning by offering structured support during the learning process. For this to constitute scaffolding it is important both that it enables the learner to achieve beyond what they could manage without the support, and that the student is then facilitated to work with diminishing levels of structured support as they develop competence and confidence. This is called fading - the scaffolding is faded as it is no longer needed (Taber, this volume).

A scaffolding structure need not be something physical - it could be inherent in a teaching sequence where the teacher modifies task design over a number of activities or lessons to shift the balance between the support provided and the responsibility taken over by the learner. In effect, the 'steps' in an activity that the learner is expected to take unaided get larger as through familiarity and experience they are able to 'chunk' more complex patterns of information within their working memory (Gobet et al., 2001). This is not just a matter of confidence, but relates to how the human cognitive system processes information such that something that seems complex and complicated to a novice (a typical learner) may be readily accessed and applied as a coherent unit of thinking by an expert (such as a subject specialist teacher).

Given that new novel conceptual structures are 'built' upon the 'foundations' of prerequisite knowledge, the process relies upon the learner activating the intended prior learning - bringing it to mind, and being aware that it is relevant to the task in hand. Often it may be important that a particular subset of the ideas about a topic previously met are activated, and that they are understood in a particular relationship (rather than as just a discrete a collection of ideas), as a starting point for the process of developing new knowledge. The present research drew upon a distinction between two types of tool that might be used as part of the scaffolding process (Taber, this volume):

- an activity to activate the relevant (expected) prerequisite learning, and check it was canonical - this type of tool is labelled a platform for new knowledge, or a scaffolding PLANK;

- an activity to help learners see how prerequisite knowledge supported a particular conceptual understanding adopted in physics - tools of this type are labelled as provided outlines offering epistemological support, or in more friendly language, scaffolding POLES.

An activity to potentially scaffold new conceptual understanding (a scaffolding POLE) was prepared to be undertaken after a short activity to reactivate expected prerequisite learning (a scaffolding PLANK). The materials were tested by asking students (n=122, c.16-17 years of age) taking the elective 'AS' physics course in England in teaching groups in five different schools to complete a paper-and-pencil activity. A

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[1] a formalism to support logical deductions, such as
(i) scaffolding requires a matching between task demand and student developmental level;
(ii) activity X is pitched too far from the students' current capacities for meaningful engagement, even with support from others;
(therefore) (iii) activity X cannot be considered to exemplify scaffolding in this particular learning context.

quasi-random process was used such that some students completed the POLES activity, and other classmates a parallel activity less directly related to the conceptual knowledge being investigated. This provided an intervention (potentially scaffolded) group and a comparison group made up from students in the same classes.

Exemplification of scaffolding PLANKS and POLES: an example from physics

Clearly the principles of scaffolding are generally applicable wherever a learner is working in the ZPD and their development can be supported by engaging in activity with more advanced others. Ideally scaffolding is a face-to-face process where the 'teacher' monitors progress and gives ongoing guidance. Classroom teachers certainly should do as much of this as is practical, but the circumstances of most formal classrooms mean that learners cannot have constant individual attention, and so structured activities, perhaps supported by texts, simulations etc., need to be used to support the scaffolding process. Such tools may not be perfect substitutes for the direct guidance of the teacher, but can, to some extent, be targeted to individual learners' needs (Brock, 2007) and so avoid some aspects of teacher-centred traditional teaching that ignores distinctions between different learners in a class.

It has long been known that teaching for rote learning and giving notes to be copied down will not effectively foster meaningful learning, and Vygotsky points out that routine exercises (as many 'problems' set for students may actually be) have limited potential for supporting development. [2] Yet the high workload of teachers in formal educational institutions often presents them with the choice of setting work within students' ZAD, [3] that is work that they can succeed at without extensive individual support, or setting work in their ZPD, which most students will fail to successfully complete because there is simply not enough teacher time to get around the class and offer the support needed. It is in bridging that chasm that activities designed with in-built scaffolding support can allow students to work in their ZPD because the learners require less direct contact from the teacher. It is within this context that an attempt was made to design, and test out the potential of a pair of scaffolding tools, a PLANK and a POLE, [4] in the context of a topic in physics known to be challenging to learners.

Exemplifying scaffolding - orbital motion

The principles discussed here can be applied across various teaching contexts. The example discussed derives from physics teaching and is particular to understanding the canonical explanation of orbital motion as a form of (approximately) circular motion. Study participants were asked the question 'Why do planets move in (nearly) circular orbits around the sun?' This question relates to some conceptual material that many students find difficult, and where it is common for students to hold alternative conceptions (Taber, 2014). The reader may (but alternatively, and quite reasonably, may not) wish to test their own understanding of the physics before proceeding by considering how they might answer this question.

The focus was on the key principles relating to how an orbit is considered in physics to be accelerated motion, which must be the result on an unbalanced force. Briefly, for those not especially interested in the physics for its own sake, student difficulties here tend to be linked to a number of sticking points. One of

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[2] In the Vygostkian perspective that gave rise to the notion of scaffolding, learning is considered to lead development - but not all learning equally supports development (see Taber, this volume). The distinction between learning and development is taken in this chapter as one of kind, yet not an absolute distinction. Learning more of the same (e.g. more examples or applications of a concept) does not usually facilitate qualitatively new skills or understanding. Learning of something more novel may however help facilitate the development of new skills or qualitative more sophisticated conceptual schemes.

[3] The abbreviations ZAD, ZPD, and ZDD are used here for both singular ('zone of…') and plural ('zones of…'), so here "…setting work within students' [zones of actual development]…", etc.

[4] To aid readability the term POLE is used as the singular of POLES (although the S is part of the generic acronym) to refer to a particular example.

these is that motion with constant velocity will continue without any force being exerted. That is, an object moving in a straight line will, when not subject to a force acting on it, continue to move in the same line, at the same speed, indefinitely. This is a core principle in physics (the principle of inertia, also known as Newton's first law of motion), but seems counterintuitive to many students, as any object they ever push, throw, pull, or drive, soon comes to a stop once there is no force acting to maintain motion. Only rarely do real-life situations approximate to the ideal situation taken as a starting point in physics - for example, an ice hockey player may appreciate conditions where a puck does not obviously slow as it moves across the ice - and it is only in such atypical situations that experience seems aligned with the principle of inertia.

This is because in the real-life situations people experience there are always resistive forces, friction, air resistance, acting against movement. To keep something moving at constant velocity, when it is subject to such resistive forces, one needs to provide an equal force to work against and cancel the potential effect of those resistive forces. This balancing force means the net force is zero, which is the determining factor: no overall force means no change in the state of motion.

One of the most well-established results in the active field of research exploring students' learning in the sciences (e.g., Taber, 2009), is that it is very common for students to hold an alternative conception about this aspect of the natural world (Gilbert & Zylbersztajn, 1985; Savinainen & Scott, 2002; Watts, 1983; Watts & Zylbersztajn, 1981). Whereas the formal physics conception relates force and acceleration (no net force, means no acceleration; net force implies acceleration in the direction of the net applied force), sometimes denoted F-a thinking; students commonly demonstrate thinking denoted F-v (Viennot, 1985): that something moving (having a non-zero velocity) must be subject to a force, and that if no force was acting on the object then its velocity would be zero. This 'alternative conceptual framework' has been identified in students of various ages, before and after instruction, in many different educational contexts. Effective teaching of the canonical science here remains a concern of physics education (Alonzo & Steedle, 2009).

When a net force is not zero, it will cause acceleration. In everyday life, acceleration means getting faster, but in physics the technical meaning is a change of velocity. That is subtly different in two senses. One is simply that an acceleration may involve a reduction of speed: deceleration is negative acceleration (acceleration with a negative value) which to a physicist is still acceleration. This may seem akin to considering a pay cut as simply a pay rise with a negative value. However, this is not such a strange way of thinking when it is realised that acceleration is an example of what is known in science as a vector - something which has a particular direction as well as a magnitude. A negative acceleration is actually equivalent to a positive acceleration in the opposite direction. Physicists generally consider choice of reference direction somewhat arbitrary as it depends upon the viewpoint adopted: passengers on two trains that happen to pass each other at a station will subjectively experience the station passing them in opposite directions.

Velocity is also a vector, and this introduces the next complication, which is that a change of speed implies a change in velocity, but this does not mean that there can only be a change of velocity when there is a change of speed. An object moving at a constant speed, but changing its direction, is changing its velocity. This is confusing to many students because they are usually used to thinking of speed and velocity as synonymous (as in common everyday use), but for a scientist there is an important difference. Indeed, if a student confused by the formalisms adopted in physics ran out of the physics class at 2 ms^{-1}, heading in an Easterly direction, and the physics teacher was asked what the student's velocity was, she could honestly answer 'minus 2ms^{-1} heading West', or even 'zero velocity North' (as the student running to East goes no further North or South): responses unlikely to persuade the bewildered student to consider returning.

This is very relevant for our present example of scaffolding because circular motion (and so orbital motion, when it is assumed to follow a circular path) offers a good example of changes of velocity without changes of speed. This means anything moving in a circle is accelerating, because acceleration is a change in velocity (which can be a change in direction at constant speed). [5]

Objects moving in a circle can experience two types of acceleration. One could, as an illustration, imagine the motion of a reflector on a bicycle wheel (the type attached to the spokes to aid side-on visibility) where the cyclist spins the wheel up from stationary until it is revolving at a constant rate. During the period where the wheel is being rotated faster, there is an angular acceleration (the angle of turn each second is increasing), and it is obvious to most people this is acceleration. When the wheel is then spun at a constant rate the angular speed is now fixed (so zero angular acceleration), but there is still acceleration due to the constantly changing velocity (i.e. change in direction). This type of acceleration is referred to as centripetal acceleration. When the wheel is speeding up there is both angular and centripetal acceleration, and when it reaches a steady speed there is just centripetal acceleration.

As an acceleration is always associated with a net force, then centripetal acceleration requires a force (which logically enough is referred to as a centripetal force). Orbital motion approximates circular motion and so involves a change in velocity (as direction constantly changes even if the speed is constant), so is accelerated motion which must be due to some force. The centripetal force is gravitational in this case: planets experience a gravitational force due to their interaction with their sun / star. The reader may be aware that actual planetary orbits are not perfect circles, but ellipses (see footnote 5). The eccentricity of real planetary orbits complicates the story, but does not undermine what has been said above. That is, this is the kind of simplification that Bruner (1960) referred to as intellectually honest, as it removes detail which does not impinge on the essential features of the system being discussed, and which can always be reinstated at a later turn of a spiral curriculum.

For many students, however, a circular orbit implies constant speed (which is the case) and therefore (as velocity is incorrectly assumed to be synonymous with speed) no acceleration (which is not the case). They usually know there is gravity acting, but may consider that the centripetal force is being balanced by an opposing 'centrifugal' force. They are sometimes aided in drawing this conclusion by a misapplication of a principle known as Newton's third law which requires that forces always occur in matched pairs (that is, they are interactions between bodies). There is indeed an 'equal but opposite' force to the gravitational force acting on the planet, but it is the force acting on the sun due to the gravitational attraction between these two bodies. [6] Errors in applying Newton's third law are common (Taber, 2000a), and in particular

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[5] The actual orbits of satellites, such as planets around the sun or the moon around the earth, are elliptical, and actual circular motion is a special case of elliptical motion. A planet moves around the sun in (approximately) an ellipse at which the sun occupies one of the two foci. The speed of the planet varies such that it moves faster when nearer the sun, and slower when further away - in a similar way to how a ball slows down as it rolls up a hill, and then speeds up as it rolls back down. The circle can be seen as a special case of the ellipse (in a similar way to how a square is a special kind of rectangle - it has four sides with right angles between adjacent sides so is a rectangle, and also all sides of equal length) where the two foci overlap, and the orbital body remains at a constant distance from the centre of the orbit (and so does not change speed). Teaching about circular orbits is justified both because real orbiting bodies often have orbits with modest eccentricity (i.e., they are fair approximations to circles) and because in terms of conceptual development, a good understanding of the special case would be seen as prerequisite knowledge for understanding the complications involved when orbits do deviate from circles. Even the elliptical orbit is an ideal, as in practice actual orbits are subject to perturbations due to other complications - such as the gravitational attraction between different orbiting bodies. For many purposes, however, such effects are small enough to be ignored.

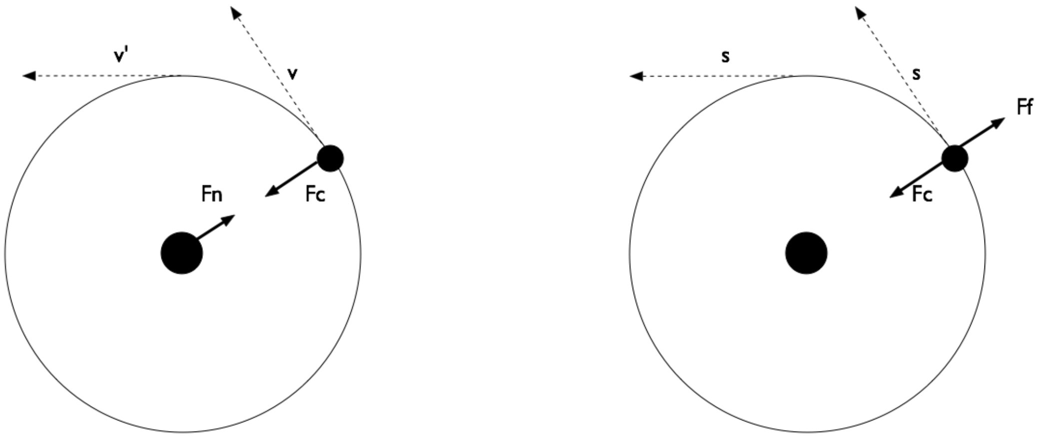
[6] The logic here suggests that rather than one body orbiting the other, they should both be 'orbiting' as a result of the unbalanced forces acting on each of them. Technically this is so and the effect may be obvious in binary star systems when two stars of similar mass orbit around a point between them. However in cases where the star is very much more massive than the satellite it is often possible to consider its motion as negligible. In considering solar systems, it is also common to adopt a frame of reference taking the star as fixed in space. This is considered acceptable (as well as convenient), as there is no absolute or neutral frame of reference in space (e.g. a solar system will be moving within its galaxy; the galaxies move in relation to each other). This is similar to how on earth we often treat the surface as having fixed locations. So London is taken as being in a particular place, whereas it actually traces a trajectory through space, not only as the Earth rotates, and as the Earth orbits the Sun, but as the entire solar system moves around the galactic centre at over 200 km each second. London today is a great distance away from where it was, say, a Century ago, in terms of its position in the galaxy.

students often make the mistake of assuming the 'paired' forces must act on the same body, even though this would imply nothing would ever change its state of motion. These key principles of Newtonian physics are summarised in Table 1, which also highlights some of the particular alternative conceptions that are common and lead to difficulties in learning the physics.

Law	Content of law	Explanation	Comment
Newton's first law (also known as the principle of inertia)	A body that is not subject to any net force will not change its state of motion	If the object is not moving, and no force acts, it remains stationary. If the object is moving, and no force acts, it continues to move with the same velocity (i.e., in the same direction at the same speed.)	People generally have little difficulty with this principle when an object is initially stationary. However, the natural attitude is to expect motion to dissipate of its own accord as if something ('impetus') is being used up
Newton's second law	The rate of change of momentum of a body is directly proportional to the (net) applied force, and takes place in the direction of the (net) applied force.	In effect, the greater the force, the greater the acceleration (change in velocity).	Students can have difficulty in appreciating that an object in orbital motion is moving in a direction tangential to the applied force. (The direction of *a change in* velocity does not equate to the direction of that velocity.)
Newton's third law	If a body A exerts a force on a body B then the body B exerts a force on body A of the same magnitude, and acting in the opposite direction along the same line of action.	In physics, force always reflects an interaction between two bodies, and acts on both.	There are several common learning difficulties here. One is to consider that the two opposing forces act on the same body.
Newton's law of universal gravitation	There is always a force acting between any two masses, which is proportional to the product of the masses, and inversely proportional to their separation.	In orbital motion the central body attracts the orbiting body, and this centripetal force continuously shifts the direction of the orbiting body so it does not move off into space.	Some students consider circular motion as a kind of 'natural' motion which does not need a cause, and so assume there must be a centrifugal force to balance the effect of the gravitational attraction.

Table 1: Some learning difficulties in relation to Newtonian physics.

The application of these principles and learning difficulties to the case of orbital motion are summarised in figure 1, which reflects both the scientific conception and a common alternative conception of the same system. The alternative conception is logically coherent, but based on common errors (ignoring the importance of direction when judging if velocity is changing; mis-applying Newton's third law in assuming that it requires paired forces to act on the same body).



Scientific conception: net force, acceleration
There is an unbalanced force (Fc) acting on the orbiting body (e.g., planet) due to gravitation attraction to the central body (e.g., sun). The planet is accelerating as the velocity is changing (e.g., v' is different from v as in a different direction).
(Newton's 3rd law requires a force to act on the sun (Fn) but this has no effect on the planet.)

Alternative conception: no net force, no acceleration
There is no overall force acting on the orbiting body (e.g., planet) as the gravitation attraction (Fc) to the central body (e.g., sun), must according to Newton's 3rd law be balanced by another force (Ff).
The speed (s) of the planet does not change, as there is no net force, so no acceleration.

Figure 1: Two conceptions of orbital motion (one linked to the curriculum, the other a common understanding offered by students).

Teaching context

The context of this study was the teaching of physics at post-compulsory level in the English school system. Students in England study a 'balanced' science (i.e., including biology, chemistry and physics) to age 16. Students then have various options open to them, to continue academic study in school, or to move to a college, or to take up some kind of vocational training. The most common academic route is a two year 'A' (Advanced) level course studying three or four subjects. This is the main qualification considered by universities for entrance to degree courses. The students in the present study were in the first year of such courses, initially working towards an intermediate qualification ('AS' level), at which point some may have chosen to drop physics or could have been counselled off the course if considered unlikely to successfully complete the A level. Students are usually only admitted to an A level course in physics if (i) they have a decent spread of good passes in the national examinations taken at age 16; and more specifically (ii) if they were awarded a good grade for their science; and (iii) a good grade for their mathematics. This population is therefore both self-selected (opting to take the academic route; opting to study physics) and selected by their school or college (meeting general entrance requirements for A level study, and the subject-specific requirements to take the physics option).

Circular motion is studied during A level physics, usually later in the course, drawing upon basic principles that will have been met during earlier school courses. The present exercise was designed to scaffold key learning about circular motion, drawing upon principles that should have been familiar to students at this level. In order to support learning here, two simple scaffolding tools were designed. In a realistic teaching situation these would be introduced as part of a teacher's presentation of the topic. Here they were trialled by asking a small number of teachers to test them out with physics classes where students had been taught the basic physics principles needed to understand the canonical explanation of orbital motion.

A tool to organise background knowledge

The first tool was intended as a PLANK (Taber, this volume) - a device to help students orientate themselves before they were asked 'Why do planets move in (nearly) circular orbits around the sun?' This simple activity asked students to complete a small number of statements by matching incomplete sentences (see figure 2) :

1. Please select the correct phrase to complete each sentence - and write the code letter in the empty column (⇓).

	⇓
acceleration is a…	
acceleration is produced by…	
an object's velocity does not change if…	
opposing forces of equal size…	
an orbit is a…	
velocity is…	

A	…balance (cancel out)
B	…change in velocity
C	…circular or elliptical path of a satellite
D	…forces acting are balanced
E	…speed in a particular direction
F	…unbalanced (resultant) force

Figure 2: A PLANK task designed to activate relevant knowledge in the context of orbital motion.

The rationale behind this task is to require students to bring to mind the relevant prerequisite physics ideas from memory, and to actively think about them in order to complete the task. This particular task is not designed to be challenging for the target group, and rather is a kind of 'warm-up' activity; but it does allow students to focus on the particular background knowledge that is relevant to the following task. Students who have this knowledge probably also know that force is measured in Newtons, that forces can spin or deform objects, that weight is a force, that forces can be measured in the classroom with spring balances, and many other things related to the wider concept of forces, but that knowledge is not directly relevant to the learning activity to be undertaken. The task is then intended to highlight (and check) the particular relevant prior knowledge that will need to be applied.

If the main activity (explaining 'Why do planets move in (nearly) circular orbits around the sun?') has been correctly targeted at students ready to consider the question, then student responses on this introductory task should be, or approach, 100% correct. Students who cannot complete this task may currently lack the prerequisite background knowledge to construct the target explanation in the following task. We might say that in such circumstances the explanation task is likely to be in their ZDD (zone of distal development) and so beyond the ZPD where success may be scaffolded. Of course, one has to be aware that some students may get the responses right more by luck than judgement (e.g., guessing) and others capable of the activity might not engage (especially if it seems too trivial) or might be careless in reading the statements or filling in their answers. In principle though, this activity can act as a filter, as a diagnostic assessment item to identify students who need some remedial learning activity before proceeding. This PLANK was presented to 122 students who 'should' have mastered these ideas (i.e. they had progressed beyond the educational stage where this was taught), in 5 classes, and 85 (70%) completed the task correctly, matching all of the statements up.

A tool to scaffold the explanation

The second tool was intended as a POLE - a structure to help support the student in building up the new knowledge (Taber, this volume), in this case in constructing the target explanation. This tool involved offering some key terms useful in constructing the explanation, and asking the student to sequence them in a particular way intended to reflect the logic of the explanation. This was done by presenting a large figure (reproduced here as figure 3) covering most of a full A4 page, with the instructions "Look at the figure below. Try to organise the six terms into a chain (see the example, right): starting with the term 'orbit' and using arrows to mean 'implies' or 'must mean that'."

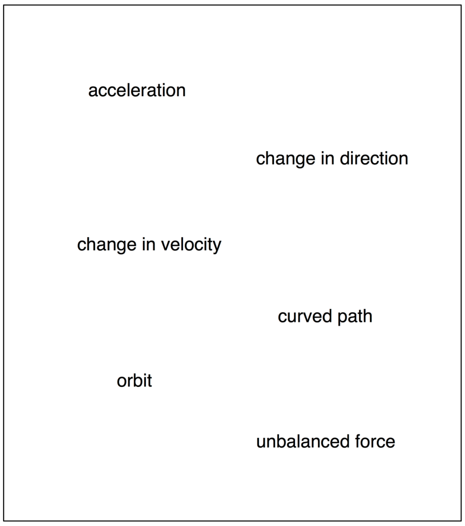


Figure 3: A scaffold for understanding orbital motion.

Students were told "A good chain will use each term once, and will produce a chain of logical connections" and this hint was accompanied by an example (reproduced here as figure 4).

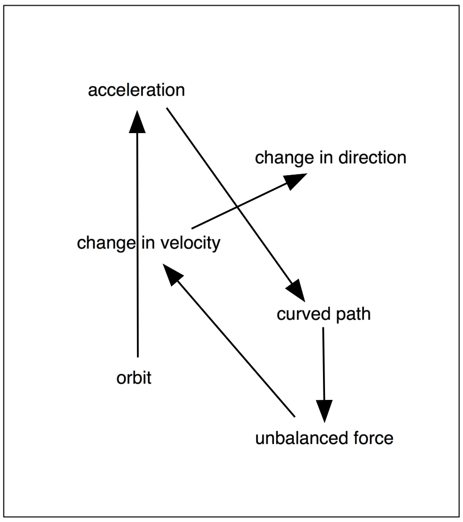


Figure 4: An exemplar (but not the right solution) offered to students.

The model response is reflected in figure 5 (which was not presented to participants). Partially complete responses could indicate understanding of the concepts but perhaps a failure to find an optimal chain where each link is sensible. The value of the POLE is primarily in engaging thinking about the ideas within a context constraining the potential 'degrees of freedom' (Pea, 2004; see Taber, this volume) when compared to the more open pre-/post-test task (i.e. providing an explanation).

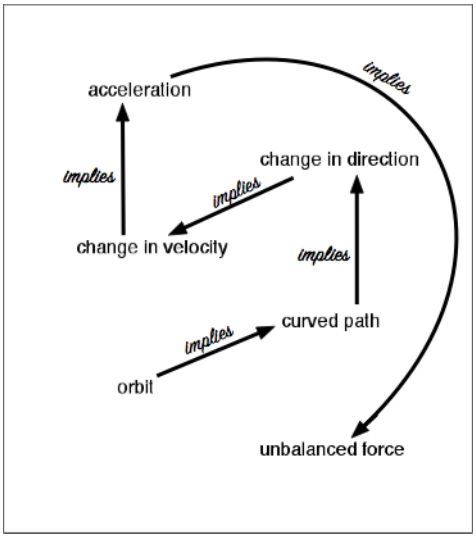


Figure 5: The model answer for the scaffolding POLE.

A smaller number of students completed this activity (for reasons explained below). It was undertaken by 59 students. Of these, 37 had successfully completed the PLANK activity. Of those 37 students, 9 (24 %) produced a response matching the model answer.

Testing the scaffolding POLE

As an attempt to test whether the scaffolding POLE had any value in supporting student learning about orbital motion, students in the intervention (scaffolded) group completed it as the third of four activities, compiled in to a paper-and-pencil type instrument:

1. PLANK activity
2. Core task: 'Why do planets move in (nearly) circular orbits around the sun?'
3s. POLES activity
4. Core task (repeated): 'Why do planets move in (nearly) circular orbits around the sun?'

The question for task 2 was accompanied by an image of a simple solar system (figure 6). The second time they were asked to give the explanation (task 4) this figure was presented again, alongside a small reproduction of figure 3.

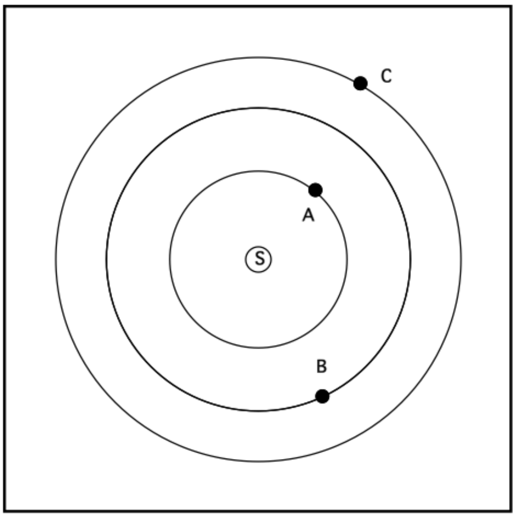


Figure 6: Image of a solar system presented with tasks 2 and 4.

That is, students were asked to offer an explanation twice - once before attempting the POLE and once afterwards. Students were asked twice as simply asking them after completing the POLE would give no indication of whether it had helped organise their thoughts or not. Of course, there are at least two complications here. One is that having just had one attempt at the explanation activity, would potentially act as a learning experience which might support a more effective second attempt. The other complication is that even good-natured students might reasonably object to putting effort into the same task twice, within a short period, without a clear rationale for doing so and without being given any useful feedback in-between. Five students wrote comments such as: 'I have already answered this question' or 'This question has been repeated' in response to the second prompt for explanation.

As an attempt to control for this, a parallel paper-and-pencil type instrument with a modified sequence of tasks was prepared for a comparison group:

1. PLANK activity
2. 'Why do planets move in (nearly) circular orbits around the sun?' (as Pre-test)
3c. Alternative activity parallel to the POLES activity
4. 'Why do planets move in (nearly) circular orbits around the sun?' (as Post-test)

The alternative activity (3c) had a very similar surface structure to the POLE (3s), and was on a related theme (space) to the explanation task, but was not considered useful in building an explanation about orbital motion. It comprises of a similar completion task (figure 7) and a similar type of instruction ("Look at the figure below. Try to organise the six terms into a chain (see the example, right): starting with the term 'moon' and using arrows to mean 'is smaller than'."), with a similar hint ("A good chain will use each term once, and will produce a chain of objects of increasing size", see figure 8).

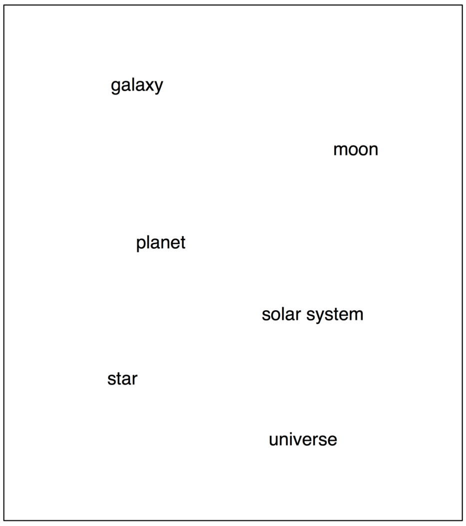


Figure 7: A parallel activity with limited scaffolding potential presented to the comparison group.

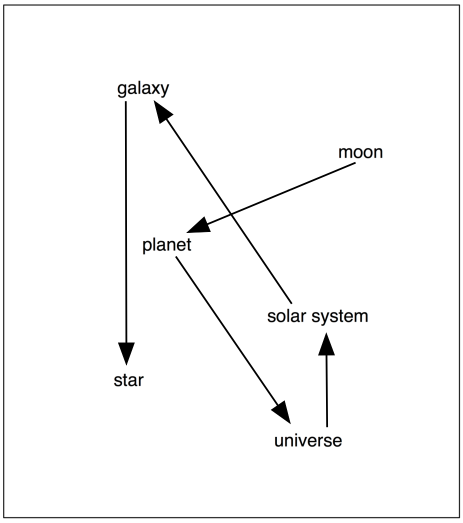


Figure 8: The exemplar response (not a model answer) offered with the parallel activity undertaken by the comparison group.

For these students in the comparison condition, the second request to provide an explanation (task 4) was accompanied by the image of the solar system (figure 6) and a smaller reproduction of the image used in their versions of task 3 (figure 7). This means the two sets of materials were structurally very similar, and only differed in the nature of task 3, and the use of the image from that task alongside the solar system image in the final task.

Teachers who volunteered to try out the materials were sent sets of the instruments with the two versions alternated, and asked to distribute them around their classes. This alternation of versions was used so that the assignment of the two versions to particular students would be arbitrary, and so in effect quasi-random.

The results of the trial

The PLANK activity was intended to have a low level of challenge, simply asking students to match the components from some simple statements, based on physics that should have previously been studied. In terms of the scaffolding process, this was intended to help students bring relevant ideas to mind, and so to consider the prerequisite learning needed for the more challenging task. In terms of the small scale study, this initial activity could be used as a filter, to eliminate students who could not access and apply the fairly basic prerequisite learning. The expectation was that few learners should fail to complete this task effectively. In practice this was found to be too optimistic. It should be noted that in a normal teaching context the PLANK activity would best be presented as a discussion task for pairs of students or small groups, which would immediately be followed by the teacher leading classroom discussion and reinforcing the canonical responses (Mortimer & Scott, 2003; Ruthven et al., 2016). In the present 'test of principle', individual working was required to collect readily interpretable data.

Here we only consider the responses of the 85 students who completed the PLANK correctly out of the total sample of 122 students. Among students who correctly completed the PLANK activity, 37 completed the POLE activity (i.e., in the scaffolded condition) and 48 undertook the alternative parallel activity (i.e., in the comparison condition). Though scoring the PLANK activity was straightforward, assessing students' explanations of orbital motion (tasks 2 and 4 in both conditions) was less straightforward, and a coding scheme to score students' explanations was developed (see Table 2). As this was a written task there was no possibility of testing (as might have been possible in an interview study, for example) whether missed steps/points were actually absent from student thinking or alternatively judged by them as implied and not required in the written explanation (Taber, 2013). This was not seen as a problem here, as this factor would apply to students in both conditions.

Element of a student's explanation
As the planet is moving in a circle its velocity is changing/as the planet is changing direction its velocity is changing
A change in direction means a change in velocity or velocity is a speed in a particular direction or velocity is a vector/velocity has both magnitude and direction
The planet is accelerating
Acceleration is (/is due to) a change in velocity
The planet must be subject to an unbalanced/net/overall/resultant force
Acceleration requires the action of an unbalanced/net/overall/resultant force
The force is provided by the gravitational force/attraction/pull from/of the sun

Table 2: Scoring scheme for students' explanations of orbital motion: Each element in the table identified in a student explanation scored one point, giving a maximum possible score for each explanation of seven points.

After coding the students' response, the points scored in each explanation were summed, and the mean scores (/7) of students' first and second attempts at explanations were calculated for the two groups: students who had completed the POLE activity (scaffolded condition) and students who had completed the parallel activity to the POLE (comparison condition). The results are shown in Table 3.

	N	Average score on first attempt at explanation	Average score on second attempt at explanation
Students completing POLE activity (scaffolded condition)	37	0.89	1.90
Students completing parallel activity to POLE (comparison condition)	48	0.96	0.85

Table 3: Summary of the average scores achieved on students' first and second attempts at explanation by participants completing either the POLE or the parallel activity. Arithmetic mean scores are shown to two decimal places.

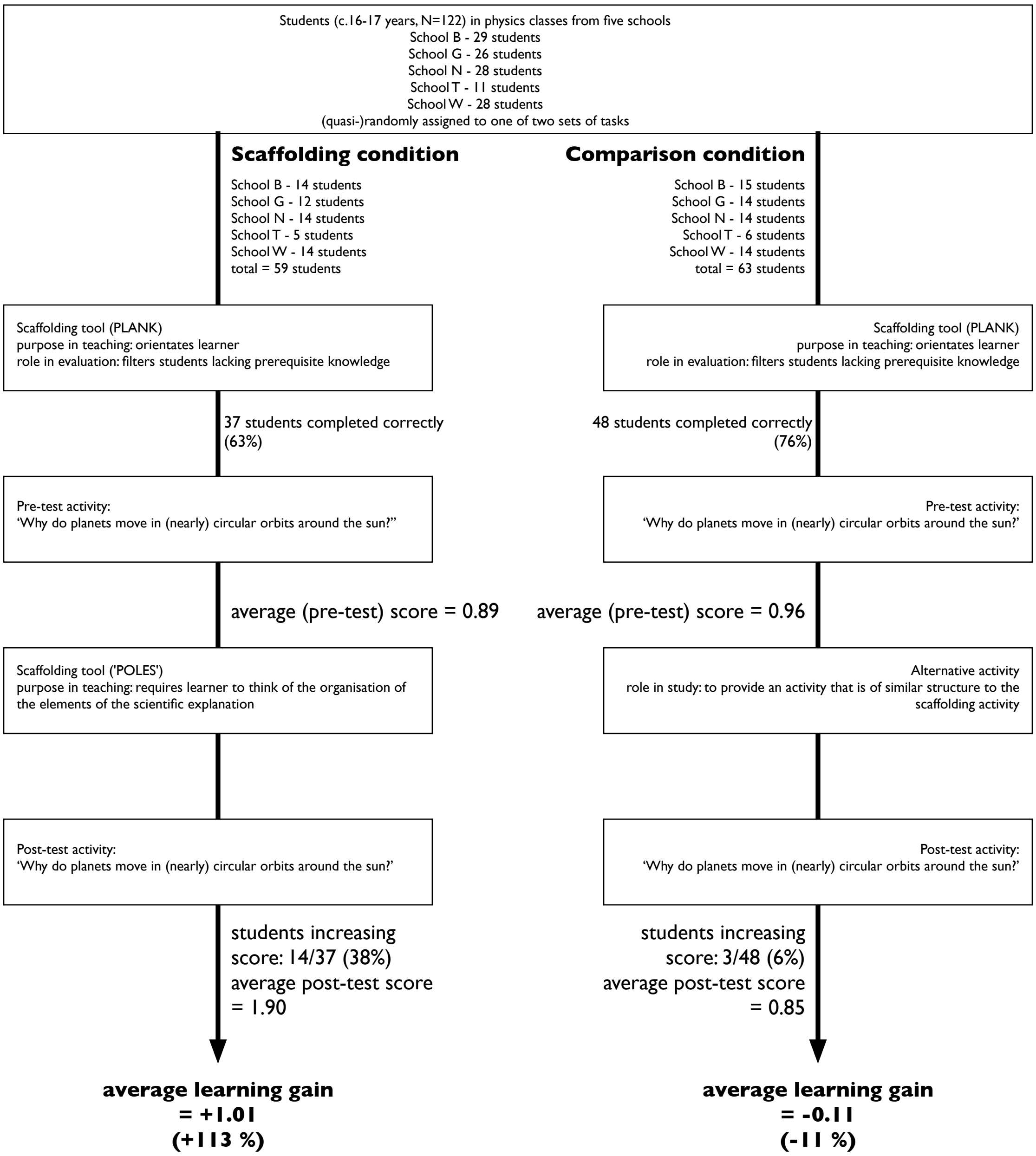


Figure 9: The overall design of the study and some key outcomes.

The data in Table 3 show that the students completing the POLE activity displayed an increase in their average score on their second attempt at explaining the orbital motion that was not seen for the students completing the parallel activity. Indeed, for those students completing the parallel activity, as might be expected in the absence of scaffolding, when asked to repeat an explanation, only three students out of 48 produced an explanation that was scored more highly than their original attempt. In the group exposed to the scaffolding task, the students' first attempts all scored one or two points. Though the majority of the students' explanations in this group (24 out of the 37 responses) remained at the same score or decreased, a more substantial number of students exposed to the POLE activity (14 out of 37 responses) produced second explanations that were scored at a higher level than their first attempt. Figure 9 summarises the design of the study, and these key outcomes.

In the group that completed the parallel task (comparison condition), students' first and second attempts at answers often displayed limited progression and the same basic argument was commonly deployed in both cases, as shown in the example below:

First attempt	The planets are held in place due to gravity. The force of gravity for planet A is strong. The speed is constant and so is the force of gravity. This enables it to be kept in a circular motion around the sun. The force doesn't really change keeping it at a fixed distance from the sun. Planet C has a smaller pull of gravity acting upon it but it still has a constant force, which will allow it to stay the same distance away from the sun.
Second attempt	The planets in the solar system are all have forces of gravity acting upon them. The force of gravity from the sun and the planet (A) is constant. As the planet orbits the sun the force is always the same meaning it is kept at a fixed distance from the sun. The velocity the planet travels at keeps it in orbit because the force is pulling the planet. The fixed velocity will not allow the planet to break from orbit.

This student deploys similar elements in both attempts at an explanation: a constant force from the sun causes the planet to orbit at constant speed or velocity; and a link is made is made between the constant force acting and an orbit at a constant distance. Another student, who completed the parallel activity, also used the construction that the sun 'holds the planets in place' in both their answers and the quality of their explanation decreased between the two probes. Such limited change to conceptualisation is unsurprising for the students who did not engage with any relevant scaffolding prompts and were asked to produce repeated explanations of the same phenomenon over a relatively short period of time. In the group that completed the activity parallel to the POLE activity (comparison condition), students' scores did not increase or decrease by more than a single point.

By contrast, a number of students in the group that completed the POLE activity produced second responses that showed substantial improvement from their first attempt, for example, in the pair of explanations shown below:

First attempt	Planets move in a circular orbit because of the star's gravitational pull.
Second attempt	Planets orbit the sun in a curved path which changes direction because of the gravity pull from the sun. This results in a change of direction which is a change in velocity which means there is an unbalance of forces which can lead to acceleration and eventually the orbit will become balanced and the planet will orbit the sun at this speed as long as the sun's gravitational pull stays equal.

This student's first answer consisted of a single link between a cause (the sun's gravitational attraction) and an effect (the circular motion of the planets). Following the POLE activity, the student wrote an explanation that includes an extended explanatory sequence that makes use of a number of abstract concepts (velocity, acceleration, unbalanced force) to link cause with effect. The initial PLANK activity indicated that this student possessed all the appropriate conceptual elements to explain orbital motion, but failed to activate them in the first response. Here, the POLE activity appears to have acted as a tool that supported the activation and more appropriate structuring of the student's existing conceptual resources. This does not demonstrate long-term learning (which would need a study design with a deferred follow-up), but it does show that on the activity facilitated the production of an explanation suggesting an understanding of the overall conceptual scheme associated with the target knowledge.

Though the POLE activity led to improvement in the quality of some students' explanations of orbital motion, for other students in the scaffolded group, the activity did little to change the level of their responses. The frequency of occurrence of explanations at different levels for the pre- and post-test in the scaffolded and comparison conditions is shown below (see Figure 10).

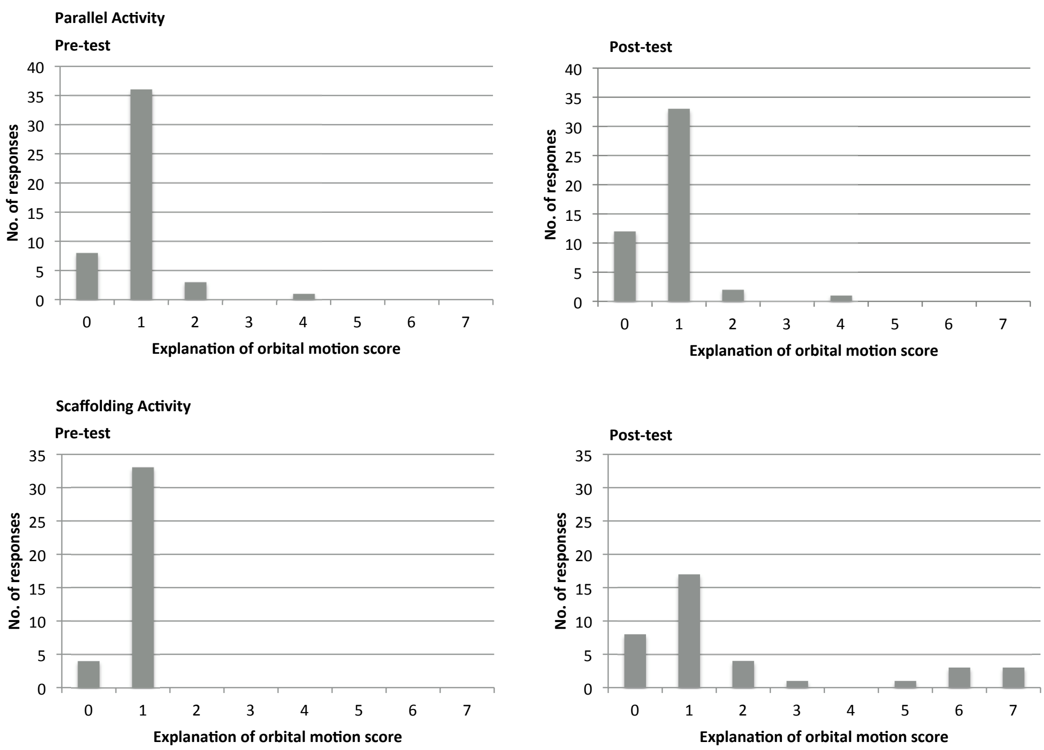


Figure 10: Representations of number of responses awarded particular scores on the pre- and post-tests for the groups completing the parallel (comparison) and POLE (scaffolded) activity.

It is apparent that for the comparison group completing the parallel activity there was only limited change to the distribution of the scores of students' explanations. However, for the 'scaffolded' group that completed the POLE activity, a substantive change to the distribution of the scores of explanations is evident. However, one striking feature of the pattern of change for students completing the POLE activity is that few increased to intermediate scores of three, four or five rather than maximum or near maximum scores. This pattern could be an artefact of the linear, sequential nature of the explanation in this context (see Figure 5). In the POLE activity, the students were asked to complete a chain linking a cause (the action of a force) to a series of different effects (for example, changes to velocity and acceleration). As this chain has a particular logical sequence, it might be imagined that students are likely to either produce a perfect or near perfect answer (scoring six or seven) or fail to score highly on the exercise. Students are unlikely to be able to link three of four steps in the explanatory process, and then not be able to add in the final few stages. This may indicate that the POLE acted as scaffolding activity for some students (in Vygotsky's terms, by engaging them within their ZPD) but not others (where the activity would be judged as falling in the ZDD).

An analysis of the students in the POLE activity (scaffolded condition) group's performance on the PLANK and POLE activity provides some insight into why the scaffolding task had limited impact on the majority of students. An illustration of the performance of the students in the group completing the POLE activity is shown in Figure 11, below.

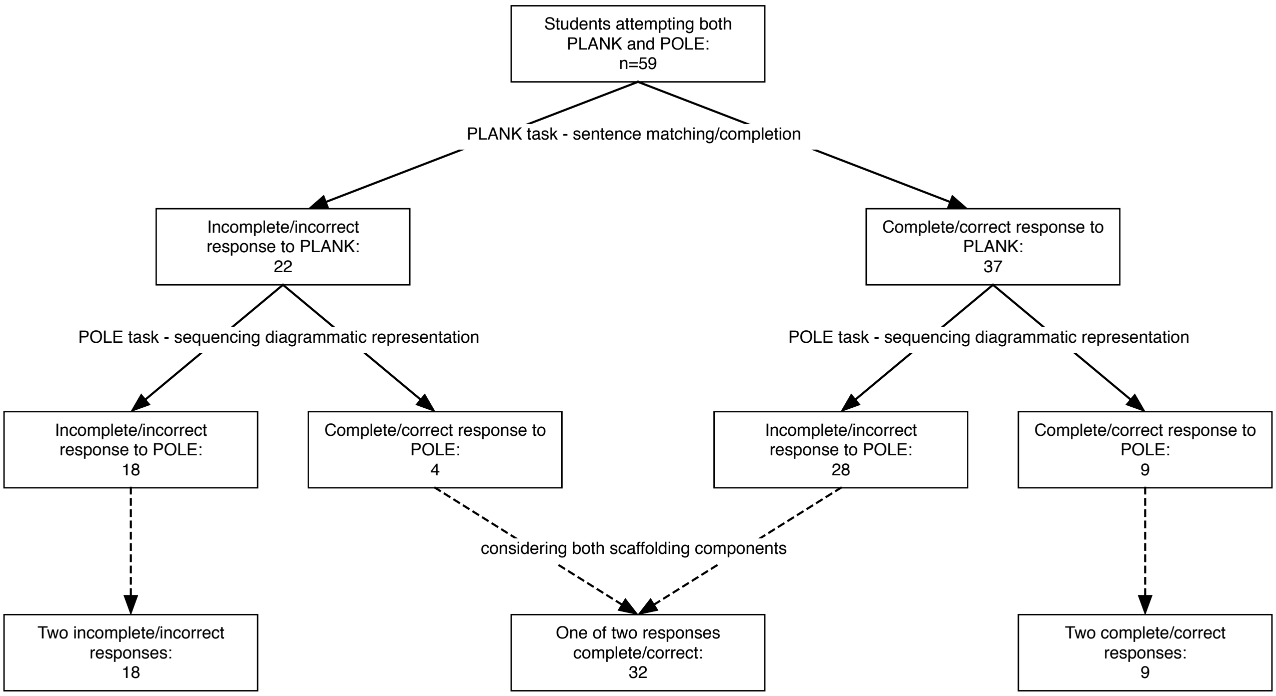


Figure 11: A representation of outcomes on the PLANK and POLE task for students in the group that completed the POLE task (scaffolding condition).

The scores of the students on the two different tasks highlight the challenge of devising scaffolding activities that can function without the direct intervention of the teacher. It had been assumed that nearly all of the students would correctly complete the PLANK activity, as it was based on concepts that the students had been taught previously: however, only 63% (37 out of 59 students) of the students completed the activity correctly. Similarly, it was hypothesised that a substantial proportion of the students completing the POLE activity would produce an answer that matched or nearly matched the model answer. In reality, only 22% (13 students out of the 59 who attempted the POLE task) produced a solution that replicated the expected answer. The unexpected level of challenge of these two tasks resulted in a relatively small group of nine students who completed both tasks correctly (see figure 11). This observation might explain why, as represented in Figure 10, a relatively small change is evident in the distribution of scores from the pre- to post-test for the group completing the POLE activity. Though only nine students completed both the PLANK and POLE task correctly, their average explanation score increased (i.e. pre-test to post-test) by 1.8 points compared to an increase in average score of 0.8 for the other participants in the scaffolded condition (i.e. those who completed the PLANK or POLE correctly, but not both; as well as those who were unable to correctly complete either).

Scaffolding can be a powerful tool for a teacher working one-to-one with a student because the teacher can adjust their responses, in the moment, to match the ZPD of the student. However, even learners in the same teaching group in a school will have significant variations in the tasks they can and cannot achieve with support. Therefore, producing a document-mediated activity that can scaffold the learning of a group of students, as was attempted in this study, is a challenging undertaking. [7]

One approach to overcoming this challenge is to prepare a number of different scaffolding activities that are suitable for students with different ZPDs, and use data from an initial assessment to assign those activities to the appropriate students. Where students are found to initially hold alternative conceptions this approach can recruit and incorporate the strategy of differentiation by alternative conception (Brock, 2007) in which students' are assessed and put into groups based on their possession of distinct alternative conceptions of a topic. [8] The groups are then set appropriate activities to support conceptual change from their initial conceptions of the concept area towards the scientific model.

An initial assessment (that diagnoses both missing prerequisite concepts, and alternative conceptions) can be used to separate the students into groups based on their initial understandings - such as, for example, those who held the alternative conception that motion at constant velocity requires the action of a net force or those that see circular motion as natural motion that does not need to be explained. These groups could then have been provided with more targeted scaffolds that took into account their initial conceptual resources.

Limitations of the study

The study was designed as small-scale exploratory enquiry. The participants were students from classes studying with volunteer teachers in five different schools - very much a convenience sample. The mechanism for distributing the two versions of the instrument in a quasi-random manner was not entirely successful: students in the comparison condition were found to be more likely to demonstrate the expected pre-requisite knowledge, so more learners not demonstrating the prerequisite learning were 'filtered out' in the scaffolding condition. Those in the scaffolding condition performed, on average, a little less well on the pre-test of the main task. Moreover, the task was found very challenging by most students - with low mean scores on both the pre-test and post-test. The match between the activity and the preparedness of the students seems to need adjusting - scaffolding should allow students to demonstrate success in learning activities, and this scaffolding task clearly did not offer sufficient support for most of these particular students in relation to this subject matter. In taking work in this area forward, there are clearly then a number of areas for development in the light of the present study.

Discussion

Before discussing the results described above, it is worth highlighting that the changes represented in students' explanations of orbital motion should not be construed as evidence of stable conceptual change. People may hold manifold conceptions of the same phenomena or concept area (Taber, 2000b), and the

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[7] The Vygotskian perspective implies that all higher level development is socially mediated - although given the symbolic tools of the language this need not be due to direct interaction. A literate person can come to understand, say, ideas about the causes of the French revolution by reading a text written by a more knowledgable other. This is mediated learning facilitated by language in much the same way as a direct conversation can be. However there is a distinction between such mediated learning - which generally operates at a level within the reader's existing capability (i.e. within a reader's ZAD) and the kind of learning which occurs in the ZPD which supports *development* of new capabilities (e.g. understanding a more complex conceptual scheme rather than just applying perviously acquired concepts). The conditions for scaffolding may sometimes occur in such an indirect interaction, but more often there will only be mediated learning at a level of existing competence. We might imagine a literate person reading about the French revolution but lacking prerequisite concepts to understand the conceptual scheme being presented by the author of the text (i.e., the explanations being offered are 'located' in the particular reader's ZDD).

[8] In terms of the interactions in solar systems, some students suggest that a sun attracts a planet, but there is no reciprocal force acting on the sun; others think that a sun and orbiting planet both experience a force, but that the planet orbits because a greater force acts on the planet than the sun; yet others suggest that the reason a planet has a stable orbit is that although the planet is attracted to the sun this is somehow balanced by the planet repelling the sun away (Taber, 2000a). It would be possible to develop materials that challenge each of these alternative conceptions.

particular conception elicited from a student in a specific elicitation context may depend upon specific cues in a researcher's or teacher's questions or probes which trigger a response in idiosyncratic ways that may not be apparent (to either the student or the person eliciting the response). The concept elicited may also depend upon a 'set' the student brings to the interaction from immediately previous experiences (i.e. what they happen to have been recently thinking about). Where people hold manifold conceptions or multiple conceptual frameworks, the particular response elicited on a particular occasion may then be contingent on a range of factors outside the control, or even awareness, of a researcher probing their thinking. As always, our research into student thinking only offers representations of aspects of their cognition which then need to be interpreted in order to posit any models of their thinking (Taber, 2013).

Consequently in contexts such as the present study, where students have two opportunities to respond to the same question and so potentially the opportunity to give different responses, it is possible that two distinct responses could represent two alternative facets of thinking about the focus, selected from previously acquired, multiple, co-existing alternatives, rather than evidence of conceptual change (Brock & Taber, 2017). Without evidence from probes over an extended period of time, it is not possible to judge the stability of the students' constructs. However, here the two probes that prompted students' explanations were identical (apart from the image reviewing the intermediate scaffolding activity in task 4), and separated by a short interval in time, during which the respondents were engaged in a particular task (either the POLE or the parallel task) which would be expected to minimise the potential of cuing of two different responses due to the influence of extraneous contingencies. The results therefore suggest that the POLE activity appears to have some potential for shifting student thinking in the short term, and so to potentially to support the development of understanding more likely to facilitate production of more canonical explanations in the longer term. To test that suggestion studies with deferred post-tests would be needed.

The students in both groups completed the PLANK activity, that is one in which they were primed to bring to mind the concepts required to develop an effective explanation in the context of orbital motion. Students who did not possess the required conceptual elements to complete the activity were excluded from the main analysis (see figure 9, and table 3). In classroom practice this PLANK could also be considered as a diagnostic assessment activity (Treagust, 1995). Once this task is completed, responses could be checked to identify learners who should be given some remedial support or experience before proceeding, as they lack readiness to productively proceed to the next activity. If an electronic version were to be used, responses could be checked automatically, and any incorrect or incomplete responses could be flagged for the teacher's attention, or even (if used as part of a digital learning package) students could be directed to a screen to review the prerequisite knowledge whilst those classmates getting the correct responses could be directed to a different screen (e.g., in this case, to the POLES activity).

It has been noted that learners may possess all the necessary concepts to make sense of a particular context, yet fail to activate appropriate resources in response to a probe or fail to develop explanations which relate concepts in a manner which matches the accepted scientific model (Brock & Taber, 2017b). This condition that has been described as a 'fragmentation learning impediment' (i.e. a problem of activation and structuring of conceptual resources), which contrasts with a 'deficiency learning impediment' in which a learner lacks critical concepts required to make sense of a context (Taber, 2001, 2014). As such, the POLE described in this chapter might be seen as an activity that potentially addresses a 'fragmentation learning impediment', that is, the students have demonstrated (in the PLANK activity) that they possess the necessary conceptual resources to make sense of orbital motion, and hence the scaffolding activity focuses on guiding their organisation of those elements into a coherent argument.

The affordance of the POLE activity in supporting students' activation and structuring of their existing conceptual resources can be seen in the response below:

First attempt	The gravity of the Sun counter-acts the energy of the planets so that they do not drift though space. The reason why they orbit is because the force of gravity and the planets tendency of its movement energy act in parallel directions

Second attempt	The force of gravity is an unbalanced force. This causes the planets to accelerate, causing a change in velocity. Thus, as stated in Newton's laws, a change in direction occurs, resulting in a curved path, and this, an orbit.

The student in this case had knowledge of the relationship between force, acceleration and velocity (as evidenced by their correct completion of the PLANK activity), however failed to activate this knowledge in their first attempt at explaining orbital motion. The PLANK activity might then be seen as priming the activation of the concepts of force, acceleration and velocity (i.e., potentially helping to reduce the degrees of freedom in terms of the range of ideas related to forces that could be brought to mind, many of which would not be productive in relation to the explanation sought), and the POLE activity considered as highlighting an approach to structuring an argument that links those concepts, so to offer access to a new conceptual scheme derived from existing concepts. Even with this prompt, a student has to have the ability of transfer the series of discrete abstracted conceptual relations activated in the PLANK activity to the context of orbital motion, and suppress any alternative understandings of motion that may be triggered.

Conclusions

The notion of scaffolding learning (Wood et al., 1976), and indeed the notion of the ZPD (Vygotsky, 1934/1986), were originally presented to the world in the context of a learner working alongside someone more advanced in their learning or development - a parent, a tutor, or a peer who has made further progress. The challenge for most classroom teachers is simply that the size of classes does not readily allow the level of one-to-one support that scaffolding might seem to require. The teacher seems condemned to either aim low and expect limited development when setting most work within the ZAD, or to aspire to a principled failure by setting work in the ZPD and then struggle to provide the additional support needed by students to construct knowledge when working outside their comfort zones. Sometimes student grouping can help, as more advanced students can be paired with those less advanced, but this itself requires careful fine-grained assessment of progress (if scaffolding through learning resources requires an accurate evaluation of any particular learner's current level of attainment, then scaffolding through peer tutoring depends upon an accurate evaluation of the levels of attainment of both partners), and needs to be undertaken in a way that the student taking the peer-tutor role is themselves benefiting by working in their own ZPD despite having mastered the activity already (Taber & Riga, 2016).

Another approach then is to link scaffolding to another of Vygotsky's key ideas - the role of symbolic tools in the communication of culture - and to design learning resources and activities that have built in scaffolding affordances - perhaps such as PLANKS and POLES. In this context the modelling may be largely achieved vicariously through carefully designed teaching materials, leaving the teacher with more time to oversee the process, and in particular to judge how and when fading of scaffolding is appropriate. The present chapter has reported a small scale empirical study exploring this idea, albeit with students working alone on set tasks without teacher interventions. The analysis of the results remind us just how much effective teaching depends upon the teacher developing and working with models of the current level of learning of students, so they can match the teaching presentation to students' current needs. In the present study the PLANK activity, which was used as a filter to identify any students lacking what was judged as necessary prior knowledge to achieve on the POLES task, resulted in something like 30% of the students being excluded from the main analysis in the study, as they had not demonstrated sufficient grasp of the prerequisite concepts. That is, it was only effectively pitched to work as a PLANK for less than three quarters of these learners.

It was also found in the study that the POLES activity only seemed to scaffold about two-fifths of the students in that condition to improve their score on the explanation task. Most students did not seem to substantially benefit from the activity. Despite this, in comparison with the control condition, it seems that (at least in this small, and not statistically representative sample) the POLES activity did have an overall effect: the average score of the scaffolded group more than doubled, even if that was from a very low base. Clearly these activities of themselves are not sufficient to allow most students at this level to work in the ZPD and develop an understanding of the challenging concept area: but it does seem that - perhaps with some refinement - they could be a useful component of a sequence of teaching activities. These scaffolding tools were only pitched correctly for something like 30% of the target students it was assumed they would benefit, and failed to scaffold the majority of the students in the nominally 'scaffolded condition' towards a new understanding. A minority of these students were able to use the POLE to conceptualise a multi-stage explanation that they could then demonstrate in a prose answer: but for most of the sample the task was too challenging for this tool to support them.

Designing effective scaffolding tools for classroom use is clearly difficult, and such tools are unlikely to ever replace the teacher. However, when teachers are faced with either largely pitching teaching within students' ZAD and settling for limited development, or setting work within the students' ZPD and inviting failure and frustration given the limited individualised attention possible in a classroom context, the development of scaffolding tools that allow the teacher to place students within their ZPD in a supported way, for more of the time, could be very valuable. There is clearly a long way to go in refining the design of such tools, and in contextualising them within productive classroom sequences (rather than 'stand alone' activities, as here in an artificial 'test' of their effectiveness). Despite this, we would strongly recommend that Vygotsky's idea of the ZPD, and the associated notion of scaffolding learning, should be adopted by teachers and curriculum developers when planning teaching and learning. Despite the widespread use of the term 'scaffolding' within teacher's discourse, actual scaffolding of learning in the ZPD that both allows a student to achieve substantially more than they could without the scaffold, and does so in a way that facilitates genuine development towards mastery, seems less common - something that is understandable given the challenge of designing such scaffolding, as seen in this study. Given the moral imperative to use students' time and efforts in classes as productively as possible, scaffolding should be more widely adopted in the form of structured support carefully matched to students' readiness to make progress. We recognise that teachers will themselves need considerable support to undertake this, and suggest much more research on the practicalities of developing classroom scaffolding is needed.

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