Taber, K. S. (2011). Patterns in nature: challenging secondary students to learn about physical laws. *Physics Education*, 46(1), 80-89. https://doi.org/10.1088/0031-9120/46/1/010

https://iopscience.iop.org/article/10.1088/0031-9120/46/1/010

Patterns in nature: challenging secondary students to learn about physical laws

Keith S. Taber

Faculty of Education, University of Cambridge

Abstract

Teaching about the nature of science is seen as a priority within science education, and has also been highlighted as a suitable context for challenging the most able ('gifted') learners at secondary school level. This paper discusses a practical session designed to introduce the idea of physical (natural) laws. The session asks students to explore patterns in three physical systems – capacitor discharge, cooling, and equilibration of pressure in two joined columns of water. These activities were chosen because they could all be conceptualised in terms of feedback cycles and exponential decay, and so had potential to show how similar patterns are found in diverse physical phenomena. The session was taught as part of an after-school enrichment programme for 14-15 year olds students who were nominated as 'gifted' by their City comprehensive schools. The session is reviewed in the light of student responses, which suggested it made suitable demands for the most able students. The session also has potential, with suitable modifications in teaching approach, to contribute to teaching about the nature of science to students of a range of abilities and ages.

Key words: nature of science, physical laws, gifted students, enrichment material, scientific models and theories, feedback cycles, practical work

Teaching the nature of science

The notion of 'scientific literacy' has become a key issue in debates about the more appropriate type of curriculum to inform the learning of science by all school pupils (Millar & Osborne, 1998). A key feature of such scientific literacy has been an increased focus on including aspects of the nature of science (NOS) in the curriculum (Clough & Olson, 2008; Hodson, 2009; Taber, 2006b): and in the English curriculum context this has most recently been represented through the phrase 'how science works' which is given a high precedence in the secondary school science curriculum (QCA, 2007a, 2007b). The present study reports on a set of activities designed to facilitate students' learning about one specific aspect of NOS – that of scientific laws.

Challenging the most able learners

Although the increased focus on 'how science works' can be seen to be linked to attempts to make the curriculum more relevant to *all* learners, it has also been argued that NOS themes provide useful contexts for challenging the most able learners (Taber, 2007a).

The first version of the National Curriculum in science in England (i.e. the version that with some modifications was in operation from about 1990 till about 2007) was criticised for, among other things, offering too limited scope to challenge the most able students. This was not because the topics included in schools science were not potentially suitable, but rather because a combination of requiring a large number of topics to be studied, and assessing pupils through a high stakes assessment system that sought objectivity (and which was used to rank schools by the percentage of students attaining moderately good grades across a modest number of subjects), led to pupils being presented with a good deal of science, but often in limited depth.

There was concern that in many schools the most able students were not being sufficiently challenged by the science curriculum, and the UK government set up targets for schools to identify and provide suitable provision for those considered 'gifted or talented'. School science departments were expected to have identified their most able students in each year group, and to have a strategy for ensuring these students were sufficiently challenged (DfES, 2003).

The study context: the ASCEND project

The ASCEND (Able Scientists Collectively Experiencing New Demands) project was set up, with support from the *Science Enhancement Programme* (SEP), to provide a suite of science enrichment activities suitable for the most able students at upper secondary level. The project was based at the University of Cambridge's Faculty of Education, in association with the City's federation of secondary schools. Four of the local comprehensive (i.e. state maintained, all ability) schools collaborated in the project by nominating 'gifted' Y10 (14-15 years old) students to take part in the project. Schools were asked to identify students who would be likely to benefit from more challenging science-related activities, and would be interested in coming to the University in their own time, but beyond this were allowed to use their own criteria for selection. We did however ask the schools to ensure an approximate parity in the number of boys and girls invited to attend. The total cohort was about thirty students; most of who attended the programme on a regular basis.

The project ran a series of seven two-hour after school sessions that ran approximately fortnightly. Y10 was selected because these students make choices about career or college options during Y11. The details of the project have been reported elsewhere (Taber, 2007a; Taber & Riga, 2006, 2007), but key points were:

- NOS was selected as one key theme for activities (with metacognition as a subsidiary theme), as it was felt the ideas involved in NOS were suitable for work demanding higher level thinking;
- tasks were designed to be under-specified, rather than having 'recipe' type instructions, as the literature suggests that the most able students benefit from open-ended activities;
- tasks were designed to be undertaken in small groups, and in sessions we encouraged students to form mixed-school and, where possible, mixed-gender groups;
- there was a deliberate attempt to set up the programme as having an adult atmosphere: with a conference style registration with refreshments, and as

> far as possible relying on student self-discipline to maintain expected behavioural standards.

The programme was directed by a member of the University staff (the author) with support from a selection of graduate students (trainee teachers, and research students working on projects in science education) acting as teaching/research assistants, making observations of sessions, and supporting the students. As we were interested in how students responded to the level of challenge, we also (with their permission) used digital recorders to record some groups of students working together.

An activity to investigate patterns in three physical systems

Each of the ASCEND activities was organised around a different core focal theme. One of the activates took as its theme the idea of physical laws – laws of nature. The session was organised around three simple practical activities:

- a capacitor discharge circuit;
- cooling of some heated water;
- water in two connected columns which could be to given an initial difference in height of water column

To provide them with some background on these activities, each student group was provided with some handouts with information they might find useful. This material provided some general information about the nature of scientific laws, and an introduction to notions of feedback.

Learning about laws

There is a good deal of research that suggests that school students generally have a very limited understanding of key features of the NOS (Driver, Leach, Millar, & Scott, 1996; Taber, 2006a; Treagust, Chittleborough, & Mamiala, 2002). For example. students may commonly think of hypotheses as little more than ‘guesses’ and theories are either considered in much the same way (and contrasted with scientific facts) or may be considered to have been ‘proven’ true. Similarly, students commonly see scientific models as intended to be scaled replicas of what is modelled: very different to the way models are understood in science.

Laws in science	Some examples of laws in science
There are many ***laws*** in science – sometimes known as ‘*laws of nature*’. The term ‘*law*’ is normally used for a *regular pattern* that has been observed, and which it believed to be a reliable finding, i.e. something that always happens. (Laws must be ‘obeyed’.) Often laws are described in terms of mathematical relationships – so that they can be easily represented in formulae and graphs. *Laws are not really the same as* ***facts*** ‘Pure water always boils at 100˚C at atmospheric pressure.’ ‘Salt dissolves in water’ Although these statements are general – they are always expected to apply – they refer to *specific* ***examples*** (water, salt), where laws normally refer to more *general* ***classes*** (e.g. all gases, all planets etc.) *Laws are similar to* ***principles*** Some scientific ideas are described as principles, and these are general ideas. They are often quite similar to laws, in that describe relationships that are thought to always apply: an object floating in a fluid displaces its own weight of the fluid (Archimedes’ principle) during any collision the total momentum of the colliding bodies remains constant (principle of conservation of momentum) ***Laws*** are not really the same as ***theories*** Theories may be closely linked to laws, but normally a theory is an explanation, whereas a law just describes the pattern.	***Hooke’s law***: *the extension of a loaded spring or wire is directly proportional to the applied load (up to a certain point)* Hooke’s law can be explained in terms of theories about the forces between the particles considered to make up the metal. ***Ohm’s law***: *the current passing through a metallic conductor is directly proportional to the p.d. across the conductor (if other conditions are kept constant)* Ohm’s law can be explained in terms of theories about the effects of electrical fields, the structure of metals, the nature of electrical current in metals. The gas laws: ***Boyle’s law****: the product of the pressure and volume (P×V) of a fixed mass of gas at constant temperature is constant* ***Charles’ law****: the volume of a fixed mass of a gas at constant pressure is increased by the same amount for each degree increase in its temperature* ***the pressure law****: the pressure of a fixed mass of a gas of fixed volume is increased by the same amount for each degree increase in its temperature* The gas laws may be explained through kinetic theory, in terms of the properties of gas molecules ***The periodic law****: if the chemical elements are arranged in atomic number, then similar chemical properties are found in elements separated by the same number of places*. The periodic law is explained by atomic theory, and quantum theory, which relate the structures of atoms to the way they interact in forming molecules etc. ***Coulomb’s law***: *the force between two charged particles is directly proportional to the product of the masses, and inversely proportional to the square of the distance between them*

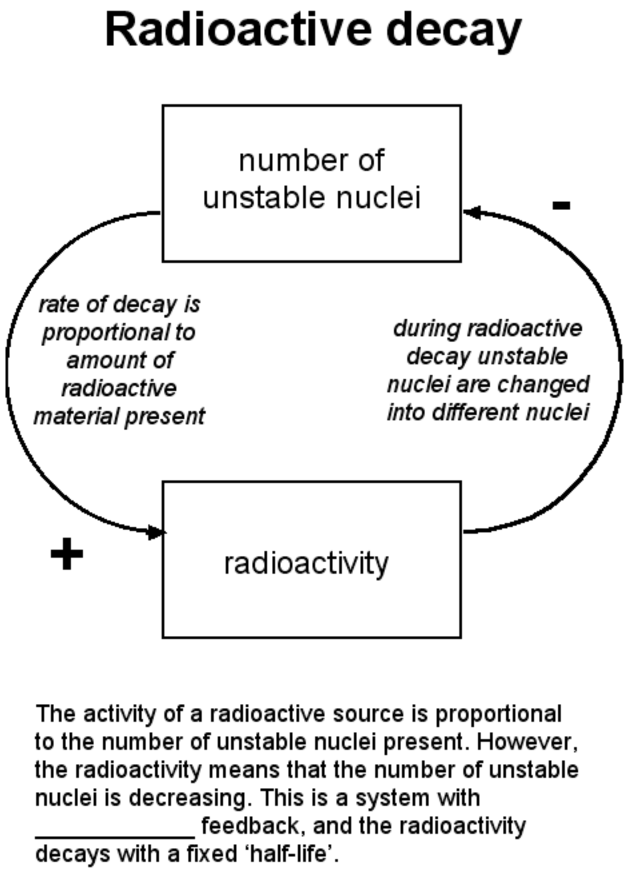
Table 1: Background information provided to student on laws

Reflections on data from an earlier study with younger secondary students in our local schools had led to a consideration of what was the appropriate level of presentation for secondary age students of such core notions as theories, models, laws and so forth (Taber, 2008). For the ASCEND session, students were provided with an A4 sheet headed 'Laws in Science' setting out an account of what laws are (and are not): this is reproduced in Table 1 (column 1). They were also provided with another A4 sheet giving some examples of laws (see Table 1, column 2).

Modelling the physical systems as feedback cycles

It was decided to introduce students to the notion of feedback cycles because understanding feedback in systems is a key idea that is applicable across the sciences. For example, homeostasis relies on negative feedback cycles to control body temperature, blood sugar and so forth. Arguments about the dangers of global warming, for example the possibility of a 'run-away' greenhouse effect, rest on the possibility of a positive feedback cycle. This idea was considered to be very relevant to the practical work as exponential decay can be explained in terms of negative feedback cycles – that is that some 'driving force' brings about an effect which inherently reduces the magnitude of that driver.

The student background information included a range of schematic representations of feedback cycles, using + and – symbols to indicate the direction of influence of the system components on each other. The figures included a series of specific examples: a howling amplifier; the body cooling itself by sweating; the warming atmosphere leading to release of carbon dioxide from the oceans; increased cloud cover in the warming atmosphere possibly reflecting enough radiation away from the earth to cool the atmosphere; consolidating learning by activating a memory trace; the relationship between science knowledge and science learning; and radioactive decay. The latter example is reproduced as Figure 1.

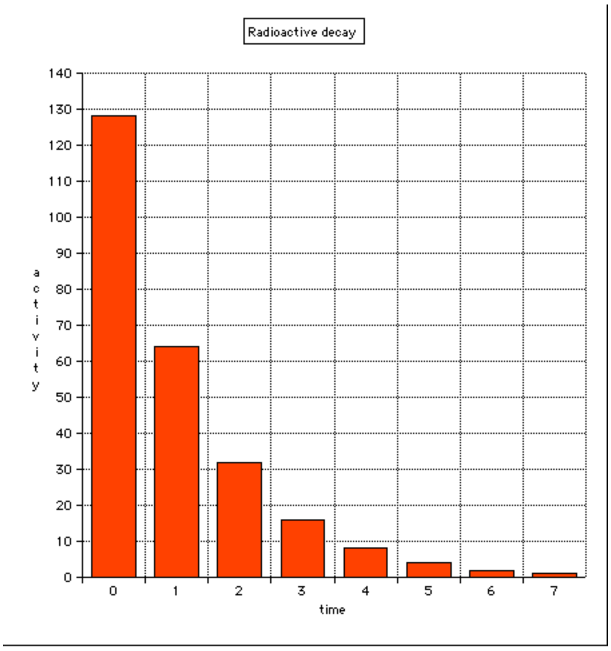


The activity of a radioactive source is proportional to the number of unstable nuclei present. However, the radioactivity means that the number of unstable nuclei is decreasing. This is a system with ____________ feedback, and the radioactivity decays with a fixed ‘half-life’.

Figure 1. Example of a negative feedback cycle: radioactive decay

Radioactive decay

The example of radioactive decay was included as something that would be met in school science at secondary level, and which could be understood as showing a decay curve. (However, as these particular students were in Year 10 of the English system, they had not all formally studied the topic.) The background information provided to students included a block-graph representation of the pattern of exponential decay of activity from a radioactive sample (see Figure 2). Although a line graph would be a more usual representation for radioactive decay, a block graph was provided to offer a more accessible visual representation of half-life.



Radioactive decay follows a pattern known as 'exponential decay'. In this type of change, the value of the measured property (activity in this case, how many radioactive nuclei change per unit time) decreases by the same proportion in a fixed period of time. So the half-life is the time take for the activity to drop to half its previous value - and it should be the same no matter where we start measuring.

Figure 2. Illustration of a decay curve provided to pupils.

The analogy across physical systems

The material about radioactive decay provided an analogy with the three physical systems to be investigated. In each case the physical process (radioactivity; current flowing from the capacitor; cooling of hot water; flow of water until water height in the two columns were equilibrated) reduced the 'driver' (number of unstable nuclei; p.d. across discharge circuit; excess temperature over ambient background; pressure difference).

As the magnitude of the process was proportional to the magnitude of the driver, the process – in reducing the driver – in effect reduced its own magnitude. Mathematically these can all be considered as exponential decays: and so they can also be conceptualised as systems with negative feedback cycles.

Practical work

In setting up the practical work it was considered important that this should not be a 'recipe-following' exercise where students are following instructions rather than thinking through the activity (Millar, 2004). The groups were provided with a one page A4 brief for each of the three tasks. In each case, the sheet gave some background on the phenomenon to be investigated, set up an enquiry question, and ask students to make a prediction before investigating. So the brief for the task with the two columns of water is shown in Table 2. The other two briefings had a similar structure.

Commentary	Text of student briefing
Heading	***Identifying patterns – water flowing downhill.***
Focal question	We all know that water flows downhill – but what determines how quickly water runs downhill?
Background to the task	You are provided with apparatus that enables you to *model* the effects of water flowing down hill. The two glass tubes are connected by flexible tubing, with a tap to stop or start water flow. You can change the difference in the height of the water in the two tubes by adjusting the clamps.
Request prediction	*Make a prediction*: What do you think will happen if you set up the apparatus so that the water in each tube is at the same height, and open the tap?
Open-ended inquiry	Check out your prediction. ***Can you identify a pattern in the water flow rate?*** Set up the apparatus to give as big a difference in water height as possible, and then open the tap to allow water to flow. See if you can identify a pattern in the rate at which the water flows from one tube to the other.
Request explanation	*Can you suggest an* ***explanation*** *for any pattern that you find?*

Table 2: Example student briefing

The task used the P-O-E (predict-observe-explain) structure (White & Gunstone, 1992). This ask pupils to make an initial prediction which is designed to elicit any expectations and existing conceptions, and to provide a motivation for making careful observations.

Student responses to the activity

The context of the ASCEND sessions was rather different to the standard school classroom context in a number of ways (e.g. attendance was voluntary, students were working in groups with students from other schools, there was a deliberate attempt to allow students more freedom to organise their work without regular monitoring and input from a teacher). None-the-less, the sessions were genuine learning contexts, with the complexity that involves: a number of groups of students working in each of several laboratories with the usual movement and noise associated with student group-work activity. Although we used digital voice recorders to collect data, this was only of limited success as students were moving about the room and were not always close to the recorders. However the graduate project assistants did make observation notes – usually following one working group throughout a session.

These data sources are drawn upon here to illustrate a discussion of the strengths and limitations of the ASCEND activity. ASCEND was a ‘research and development’ project, where we wanted to test out how ‘gifted’ students would respond to challenging, somewhat open-ended, activities, during which they would be expected to take responsibility for monitoring and regulating their own work in small groups. The context was clearly an informal extra-curricular activity, designed to be distinct from ‘typical’ school science fare, which it has been suggested is often lacking such challenge for the most able students (Taber, 2007b). Given this context, it was inappropriate for the teaching team to seek to direct (and redirect) student work in the way that might have been expected in a school classroom. If the session is adopted for use during a normal school classes, it could be modified to better suit more formal teaching contexts.

A problem with the idea of the ‘gifted’ student

It should also be pointed out that the whole notion of what is meant by a ‘gifted’ learner is contentious (see Taber, 2007b for a more detailed discussion). However, within the English context in which the ASCEND project was undertaken, schools were expected to nominate an identified cohort of ‘gifted’ students, based on a diverse and sometimes vague set of criteria. In the ASCEND project we invited schools to nominate the students they felt would most benefit from the programme, and whilst it was clear some of the delegate were intellectually very bright and would meet rigorous criteria for being gifted in science (Gilbert & Newberry, 2007), most seemed to be better characterised as students of above average attainment, with a good attitude to school study, but no obvious signs of having exceptional ability.

Student feedback on the programme

Overall, the project sessions were found to be successful in that most students were engaged in the tasks during sessions, and gave positive feedback at the end of the programme. In particular students reported liking (Taber & Riga, 2006):

- the group work (and would have like more practical activities like the one reported here);
- meeting ideas that were outside the usual school curriculum for their age group; and
- being asked to engage in more complex thinking.

The 'participant observations' made by the author and the team of graduate assistants of the particular session on laws supported the student's own reports of this being an enjoyable and engaging activity.

Student thinking and learning during the activity

Whilst the activity was certainly successful in terms of engaging students, and so valuable from a motivational perspective; our evaluation of the extent of student learning in the activity was more qualified. We observed that groups varied considerably in the efficiency of their organisation of their work; and in the extent to which they linked activities to theoretical ideas.

Organising enquiry

In view of the aim to challenge the most able students, and provide some scope for creative and individual thought, the ASCEND activities were all designed to be somewhat open-ended or under-specified. In the activity on laws, the students were given general instructions for each of the three exercises, but were not given precise details (e.g. how often to take measurements), nor told how to coordinating work across the three tasks. Whilst this reflected the intention to fit the session for students considered 'gifted' (West, 2007), it is important that *all* students are given opportunities to do practical work that goes beyond recipe-following to learn something about the nature of authentic scientific enquiry (Millar, 2004).

The student response to this level of autonomy was varied. Unsurprisingly, students seemed unused to being given freedom to set their own priorities and to make decisions about how to collect and record data. We observed one group that began with the capacitor discharge experiment, and were happily sitting talking about alternative and direct current, and the flow of electricity around a circuit, as they apparently waited for the capacitor to completely discharge without any concern that they could have a rather long wait.

Some group decision-making seemed to involve one individual simply giving instructions to peers on what to measure, without discussion; and some groups seemed to simply accept measurements without any critical engagement with potential set-up flaws or whether their results made sense. In at least one group there was an urgency to get onto the practical work that led to insufficient attention being given to any prior reading of the session handouts.

However, other groups seemed better able to take on the extra degree of responsibility for their work. One group trying to make sense of the capacitor discharge activity referred to the handouts and discussed what the difference between the two types of feedback was:

> Boy: Positive feedback is like what happens - if something happens - it causes itself to – [happen] more, isn't it?
>
> Girl: Negative, because it's like, if you think of it like a cycle it's increase – decrease…[then later] maybe it's that half-life thingie - it goes down by half and then the distance halves again and halves again and halves again.

The group agreed that the discharge process was slowing down, but did not feel they had the data to support a definitive conclusion. They decided to repeat the practical activity, now that they felt in a better position to appreciate any pattern. After repeating the experiment, the girl who spoke before suggested that,

> "I think I'm actually getting part of it now because if the capacitor's releasing current that's why it goes down faster at the beginning, cos it's more efficient. As it begins to run out of charge it - it goes slower and that's what I'm trying to understand"

A second boy in the group took up her thoughts,

> "So when it's fully charged it's releasing lots fast, but then it loses more charge which means - that it must slow down - which means that it then loses less charge than before, which means it keeps slowing down."

Identifying patterns

Whilst not in precise technical language, this comment reflects the type of physical pattern spotting that the session was intended to facilitate. From a physics teacher's perspective, the ASCEND session offered three practical activities which presented analogous patterns of change, along with a theoretical description of a fourth comparable phenomenon. Yet it is well known that learners commonly construe practical observations in completely different ways to those intended (Driver, 1983). The teacher readily 'sees' the pattern that is expected in a practical activity: but this reflects the way perception is always an interpretation of current experience in terms of existing ways of thinking. Data collected by school pupils is seldom so obviously an example of the intended physical pattern *to the learners themselves*, unless teachers carefully structure the activity to strongly support the desired interpretation.

This was reflected in the ASCEND session. However, we also collected evidence that some of the physical ideas underpinning the sessions were recognised during the activities. For example, one boy was recorded explaining his group's results from the water equilibration activity by referring to how the graph shape was "to do with pressure…as it [the water level] gets closer to the other there's less pressure, so it would slow down".

Another group seemed to recognise the asymptotic nature of the curve obtained in this activity,

> Boy 1: It'll take ages for it to go equal.
>
> Boy 2 :If it was like accurate, it would never end up equal - if you've got a curve like that it never ends up equal, because it keeps curving and going slower and slower and slower and it never quite gets to zero.
>
> Girl 1: So what do you think's going to happen when we open the tap?
>
> Girl 2: The tap is open, isn't it, and nothing's happening.
>
> Boy 2: Yes it is! It's very slowly going together - it's going slower and slower.
>
> Girl 1: So we're basically saying that it gets slower as they get closer.

In a group looking at the cooling activity, one boy commented that "when it loses heat [to] the air it means that the liquid is closer to room temperature, it means it loses less heat". Interestingly, in one group the discussion of the cooling curve led to the development of an explanation for why "the temperature drops less each time" in terms of a feedback cycle, although with the 'wrong' driver:

> "It's [be]cause there's - well, I don't know if it's right , but - smaller proportion of particles - all the particles have lots of heat energy. You have all the particles with enough energy to escape, they go quite quickly, so then less particles are escaping each time - there's less with high energy left - less and less escape and therefore the temperature changes less each time - there are a smaller number of particles with enough energy to escape."

Evaporation was not the prime mechanism for cooling in the activity, but this demonstrated an appreciation of how negative feedback works.

Adopting key ideas

For these upper secondary students, there was a lot that was new in the ASCEND session. Many would not have used circuits with capacitors before, and indeed the apparatus to look at water flow is not a standard school set up. Moreover, ideas about feedback cycles, whilst being very important in science, are not commonly studied in any detail at this level. Arguably, the introduction of 'interdependence' as an officially sanctioned 'key idea' in lower secondary science in England (Key Stage 3 National Strategy, 2002), could have been an excellent opportunity to start building learning about systems. However, despite the suggestion that 'interdependence' was a key idea *across* lower secondary science teaching, the official guidance only focused on its application to ecological topics.

Exponential decay becomes a very important concept in post-compulsory education, where the similarity of the idea across contexts can be demonstrated through the commonality of the basic mathematical function. In the ASCEND project is was hoped to give students a feel for how such structural analogies may be found in different areas of physics, using an alternative approach.

In normal teaching contexts, students will expect much more direct exposition of what they are expected to learn, something that was perhaps reflected in the comment "what's that got to do with anything?", offered by one student when it was suggested that the materials on radioactive decay might help them make sense of their results. Yet, as we have seen above, other groups did respond to this challenge.

Lessons learnt and recommendations for practice

The ASCEND materials (Taber, 2007a) are available from SEP for other teachers who may wish to adopt or modify them for use with their students. The ASCEND materials were developed primarily for use in an extra-curricular context, to support schools in challenging their most able science learners. In that context, offering something to maintain interest for students who find mainstream school science routine was more important than teaching particular concepts. The programme worked well in affective terms. Although we found that some of these 14-15 year olds responded well to the challenges set them, the demand of the sessions seemed too high for some of the students to learn optimally without more structured instruction. It would seem this was in part a matter of how English schools are expected to identify a cohort of 'gifted' students as a minimal percentage of a year group; and also in part because some of the students attending seemed to have limited skills for organising and regulating their own work. That might say more about the nature of much secondary school experience than about *the potential* of the students to cope with the work.

Teaching about NOS (or 'how science works') is becoming a more central theme of much science education, and the nature of physical laws would seem to be one important focus. The parallels between analogous laws found in different areas of physics offers an insight into the nature of the physical world; and the activity discussed here provides a way of demonstrating this without formal mathematics. This allows the work to be carried out by students who have not met the maths (as here). It also a useful approach because it has been argued that students' learning of physical concepts is improved when they show good qualitative understanding of physical concepts, *before* they are taught the associated mathematical formalisms (Ploetzner, Fehse, Kneser, & Spada, 1999).

It is suggested that the materials discussed here may be useful to teachers, providing that the provisos in this paper are considered. The session to introduce physical laws worked well with those 14-15 students who were not being sufficiently challenged by standard school science, and has potential to be used effectively with other students of this age in a more structured teaching context. The session could also be suitable for adoption or modification to introduce NOS ideas with slightly older students taking physics on pre-University courses - as the three practical activities are easy to set up, but help illustrate some profound features of the physical world.

Acknowledgement is due to the Gatsby Science Enhancement Programme for funding the ASCEND project; and to the staff and students who participated from Chesterton Community College, Cambridge; Netherhall School and Sixth Form College, Cambridge; Parkside Community College, Cambridge; and St Bede's Inter-Church Comprehensive School, Cambridge. The project was supported by Philip Anding, Richard Brock, Hannah Burleigh, Clare Burton, Frank Flegg, Alejandra García-Franco, Andreas Georgiou, Jonathan Norris, Claire Pearson, Joanna Poddar, Fran Riga, Samantha Smith, and Laura Wilson: who acted as graduate teaching assistants. Fran Riga also acted as the project's research assistant, collating data, and transcribing recordings used in the preparation of this paper.

References:

Clough, M. P., & Olson, J. K. (2008). Teaching and assessing the nature of science: an introduction. *Science & Education, 17*(2-3), 143-145.

DfES. (2003). *Teaching able, gifted and talented pupils Module 4: Science for gifted pupils*. London: Department for Education and Skills.

Driver, R. (1983). *The Pupil as Scientist?* Milton Keynes: Open University Press.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young People's Images of Science*. Buckingham: Open University Press.

Gilbert, J. K., & Newberry, M. (2007). The characteristics of the gifted and exceptionally able in science. In K. S. Taber (Ed.), *Science Education for Gifted Learners* (pp. 15-31). London: Routledge.

Hodson, D. (2009). *Teaching and learning about science: Language, theories, methods, history, traditions and values*. Rotterdam, The Netherlands: Sense Publishers.

Key Stage 3 National Strategy. (2002). Framework for teaching science: years 7, 8 and 9. London: Department for Education and Skills.

Millar, R. (2004, 3-4 June 2004). *The role of practical work in the teaching and learning of science*. Paper presented at the High School Science Laboratories: Role and Vision, National Academy of Sciences, Washington, DC.

Millar, R., & Osborne, J. (1998). *Beyond 2000: Science education for the future*. London: King's College.

Ploetzner, R., Fehse, E., Kneser, C., & Spada, H. (1999). Learning to Relate Qualitative and Quantitative Problem Representations in a Model-Based Setting for Collaborative Problem Solving. *The Journal of the Learning Sciences, 8*(2), 177-214.

QCA. (2007a). *Science: Programme of study for key stage 3 and attainment targets*. London: Qualifications and Curriculum Authority.

QCA. (2007b). *Science: Programme of study for key stage 4*. London: Qualifications and Curriculum Authority.

Taber, K. S. (2006a). Exploring pupils' understanding of key 'nature of science' terms though research as part of initial teacher education. *School Science Review, 87*(321), 51-61.

Taber, K. S. (2006b). Teaching about ideas and evidence in science – towards a genuinely broad and balanced 'science for all'. *School Science Review, 87*(321), 26-28.

Taber, K. S. (2007a). *Enriching School Science for the Gifted Learner*. London: Gatsby Science Enhancement Programme.

Taber, K. S. (2007b). Science education for gifted learners? In K. S. Taber (Ed.), *Science Education for Gifted Learners* (pp. 1-14). London: Routledge.

Taber, K. S. (2008). Towards a curricular model of the nature of science. *Science & Education, 17*(2-3), 179-218. doi: 10.1007/s11191-006-9056-4

Taber, K. S., & Riga, F. (2006). Lessons form the ASCEND project: able pupils' responses to an enrichment programme exploring the nature of science. *School Science Review, 87*(321), 97-106.

Taber, K. S., & Riga, F. (2007). Working together to provide enrichment for able science learners. In K. S. Taber (Ed.), *Science Education for Gifted Learners* (pp. 182-196). London: Routledge.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*(4), 357-368. doi: 10.1080/09500690110066485

West, A. (2007). Practical work for the gifted in science. In K. S. Taber (Ed.), *Science Education for Gifted Learners* (pp. 172-181). London: Routledge.

White, R. T., & Gunstone, R. F. (1992). *Probing Understanding*. London: Falmer Press.