[P3] Epistemology, teaching, and assessment in physics

David Sands
Department of Physical Sciences
University of Hull
d.sands@hull.ac.uk

Using epistemology to help define a teaching and assessment strategy in science is not new (1). However, science is usually seen as a homogeneous activity, leading to a single, universal epistemology which places observation at the heart of scientific endeavour. In this paper I argue that this epistemology applies much more to chemistry and biology than to physics, which from the Renaissance onwards has driven, and been driven by, developments in mathematics. Therefore observation plays a fundamentally different role in physics than in these other sciences, because physics, and physics alone, is based on deductive, and therefore predictive, mathematical descriptions of the physical world that often precede experimental observation.

The relationship between mathematics and physics dates back to the earliest days of the Renaissance. Aristotle's physics dominated at that time, but it was not physics as we know it today. In fact, a modern physicist reading Aristotle now would probably have difficulty recognising the subject. Aristotle was a philosopher and his essays are philosophical discourses, quite without any overt mathematical content. It was really Galileo who began the process of quantification, by making careful measurements which he likened to 'book keeping' (2). In Galileo's time measurements, units, and errors were not well developed. He famously measured the period of a pendulum using his pulse, for example, and had to develop his own mathematical techniques to analyse his experiments.

The relationship between mathematics and physics goes much deeper, however. Galileo's contribution was to use and develop mathematical ideas to aid the experimentalist, but it was Descartes (2) who developed the philosophy that physics should proceed by developing mathematical models of real world phenomena in order to make deductions about the world. This is an intellectual act of creativity that simply does not occur in other sciences. We understand and define the world in mathematical terms. Within classical physics it is possible to see a one-to-one correspondence between these mathematical models and physical phenomena, but since the advent of the quantum view, and even the relativistic view to some extent, the exact relationship has become less clear. It is not possible to see a wave function, for example, nor to be sure even that one exists separate from the mathematical reality. We can only be certain that we observe wave-like behaviour, but even this is a mathematical definition.

Other sciences do not work in this way, but a single epistemology is assumed. Consider Gowin's 'vee' diagram, which is a well known heuristic used in college programmes in the US [see ref 1], though not so well known in the UK. The 'vee' diagram has been used in a very wide range of applications, including high school physics experiments, and the educational claims made for it are extensive. The idea is that students should organise their thoughts about an experiment into a single page format according to epistemological considerations, thereby freeing the instructor from the difficulty of trying to assess at once the experimental competence, the critical thinking skills employed in the analysis of the experiment, and the report writing skills.

This system places observation at the centre of the epistemology, because the diagram is so constructed as to move the attention from the focus question, ie the purpose of the experiment, down to the objects and events at the heart of the observation. From here it is possible to consider either the methodological sequence or the conceptual sequence, two paths that together make up the 'vee'. Gowin intended that the practitioner is not restricted to this hierarchical, sequential, and linear movement, but should use both sides of the 'vee' interactively. However, it is not clear how this works in practise. In many of the examples quoted in the literature not all of the headings on the conceptual side are used, but progression from 'concepts' through to 'principles' and up to 'philosophy' is clearly hierarchical.

This sort of structure clearly suits sciences where observation is key to the conceptual process. Prior knowledge claims are taken into account in the focus question and in the principles, but it is essentially retrospective. Having made the observation, the prior knowledge claims are assessed in the light of the findings. Of course, this process also occurs in physics, but there is a crucial difference. Physics rests upon the twin pillars of theory and experiment, which exist side by side in equal importance. Without data, theory is nothing but conjecture, but without mathematical methods physics would have none of its predictive power. Facts, as derived from observation, are subsumed into principles, but the principles form a body of prior knowledge that informs the experiment.

The experiment itself is an act of creativity. It is a complex process using equipment which has itself been built on sound mathematical principles. Observations in other sciences, including chemistry but especially biology, are often passive, however. They involve simply seeing what is already there. That is not to say that the modern chemist does not use complex instruments, but there is still a very important place for the test tube. Observations such as these stand alone as a fact upon which hypotheses and models can be based. Rarely do such observations occur in physics.

This epistemology has two important consequences for physics education, both for the way that mathematics is taught, and for the way that we teach and assess experimental skills and understanding. Mathematics in physics can be described by a three-step model which resembles very closely a problem-solving algorithm first developed in 1943 and described in detail by Halford3 in which it is necessary to: translate the problem into an equivalent model; operate on the model; and then re-translate back to the physical situation. For the greater part of the twentieth century a great deal of emphasis was placed on mathematical competence, because analytical methods required it. Today, numerical computation can replace much of the analysis but the encoding and decoding still need to be done. Emphasis on mathematical descriptions of physical phenomena is an important outcome of this epistemology.

In the laboratory we want to assess how well the students have performed the task of understanding the key concepts and background information, and how effectively they have analysed the outcomes of the experiments in terms of this knowledge. This assessment ought to be formative, rather than summative, and, like Gowin's vee diagram, complementary to existing assessment strategies, such as reports, which only partially assess these skills. The epistemology identifies the following as being important *before* the experiment is conducted: the focus question; key prior knowledge, for example important papers or results; important concepts involved in the experiment; the methodology and equipment; the anticipated outcome, if applicable, so that it is clear about what is being measured and why. After the experiment, the student would ideally identify: any concepts required but not identified at the outset; new concepts introduced during the evaluation of the data; changes to the methodology identified in the course of the analysis; the outcome of the experiment; the relationship between the outcome and the prior conceptual understanding. Some of these may not be possible, depending on the experiment, but it is an essential aspect of the epistemology and part of the training that students should at least be aware of the ideas.

REFERENCES

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