



## “ON THE OTHER SIDE OF THE BARRIER IS THINKING”

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**Abstract:** Science requires imagination nourished by knowledge, experience and sustained critical thinking. Science teaching has the same requirements, but metacognition is even more important to a teacher than it is to a practitioner of science. Critical thinking is essential to both science and science teaching: in either domain, imagination relies on sustained critical thinking based on relevant knowledge. Knowledge can be acquired by the prepared mind, but the capacity to think must be nurtured and exercised. The raw material of critical thinking is comprehension of fundamental processes rather than knowledge of facts. In parallel with the rapid growth of scientific knowledge, there has been a tendency to focus on content rather than developing the skills needed to do science. In essence, what has been neglected is critical thinking.

**Key words:** cognitive development; critical thinking; imagination

### 1. Introduction

The patterns of thinking of most students differ greatly from those of their teachers and practising scientists [9]. Scientists learn the concepts of science, develop mental models of the phenomena observed and, based on what is known and can be surmised, evolve questions that can be answered by experiment, mathematical analysis or observation. Almost inevitably, the answers obtained prompt yet more questions. Scientists live with uncertainty; “[n]o man who has the scientific temper asserts that what is now believed in science is *exactly* right; he asserts that it is a stage on the road ...” [39]. Most post-primary students are far more certain an answer exists that is (or should be) known to their teacher and, especially, that there is *only one* answer. Few practising scientists share the latter belief, despite, perhaps, being convinced that answers exist even if they are not known (consider Fermat’s last theorem, which waited 357 years for a proof).

The research cycle of question, analysis and response requires imagination, perseverance and, especially, critical thinking: the known must be distinguished from the unknown; the illusory and the authentic have to be identified; generalisations have to be appreciated; and logical choices must be made. While it is widely agreed that critical thinking is vital, there are many different definitions of what constitutes critical thinking [1]. Ultimately, however, imagination, intuition and ‘educated guesswork’ are necessary to move beyond the purely rational and develop novel concepts [19, 33]. Einstein is reported to have said that “[i]magination is more important than knowledge. Knowledge is limited. Imagination encircles the world” [43]. Imagination and knowledge are connected by sustained critical thinking.

Bruner [8] suggested that “[l]earning something in a generic way is like leaping over a barrier. On the other side of the barrier is thinking. When the generic has been grasped, it is then we are able to recognize the new problems we encounter as exemplars of old principles we have mastered.” Science teaching is often more focussed on learning specific content than on understanding science and developing the thinking required. By focussing on content, in which specific examples are emphasised, if only by implication, we deprecate generic concepts and the thinking that represent the real power of science and make it relevant to everyday life. In this respect, students are not assisted over Bruner’s barrier.

The role of critical thinking in science education depends on the underlying intention [22]. Secondary science education is usually focussed on developing science literacy, whereas tertiary science education tends to be focussed more on the training of scientists (of course, this represents just the beginning of the training of a scientist). The difference between the two is the balance of the content, practice and impact components described by Paisley [31]. Nevertheless, critical thinking is essential

to the practice of science and to the development of an understanding (rather than just knowledge) of the content. For this reason, critical thinking is an intrinsic part of all balanced science education.

Both the practice and teaching of science rely on imagination, which arises from a sustained application of critical thinking based on knowledge. If students are to develop an appreciation of science as a useful and useable developing body of knowledge it is necessary to expound a more balanced view, involving science content, science practice and the impact of science. The best way to achieve this is to ensure that students see science in action in the classroom rather than just learning content.

## 2. Critical thinking in science

Science is commonly thought to be a purely logical activity. This view is particularly prevalent among students, partly because in teaching science we emphasise the logical arguments rather than the history of the development of concepts, which can be tortuous [27, for example], and a rigid format, which is not peculiar to science [15]. This approach perpetuates the impression conveyed in the technical literature, which Medawar [28] described as "... a totally misleading narrative ...", and in textbooks [4, 37]. While the reasons for this are understandable, it leaves an erroneous impression of the nature of science.

Logical thinking forms only part of the intellectual requirements of science. An experimental scientist needs to be able to analyse data, accommodating the likely error, and develop questions and hypotheses on the basis of the analysis and the relevant literature. While this involves logic and mathematical thinking, these tools alone are insufficient [30]. Similarly, a mathematician certainly requires logical and analytical thought, but something more is also necessary [19, 34]. Poincaré [33] called this 'intuition', which he described as "... the instrument of invention", and Polya [34] called it the 'inductive attitude' which "... aims at adapting our beliefs to our experience as efficiently as possible. It requires a certain preference for what is matter of fact. It requires a ready ascent from observations to generalizations, and a ready descent from the highest generalizations to the most concrete observations. It requires saying "maybe" and "perhaps" in a thousand different shades."

There are many examples in science in which precise models have been deduced from relatively imprecise data. For example, the atomic composition of molecules was limited by the capacity to obtain accurate masses and simple compounds [21] and Mendel's experiments did not yield perfect ratios [29]. Frequently a scientist needs to be able to look beyond the data, using the observed values to try to identify the actual values approximated by the data.

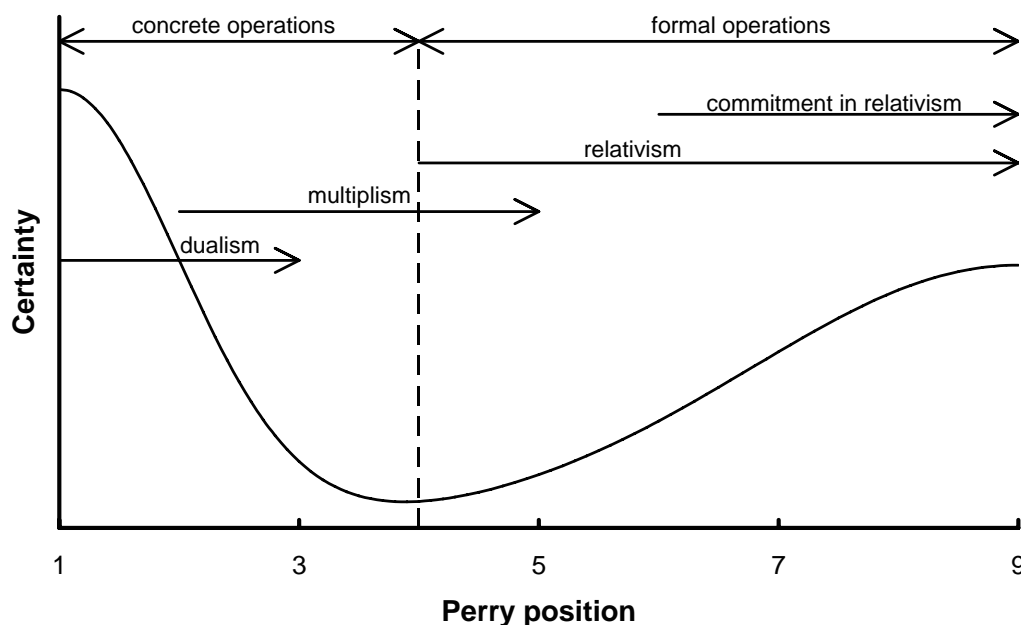
Critical thinking inevitably involves evaluating arguments, but also requires an ability to obtain and assess information and to clarify meaning [25]. Importantly, it requires an ability to move between approximation and rigour and to decide which is appropriate to the circumstances [34, 39, 40]. These abilities are not common among students.

## 3. The cognitive development of students

An understanding of the cognitive development and the prior knowledge of the students must influence both the content and the approach and expectations of the teacher. The development of critical thinking is often assessed using Perry's model (Figure 1). A dualist (positions 1 and 2) prefers structured classes and to be told the right answer, and may regard the teacher as the ultimate authority. A multiplist (positions 3 and 4) may distinguish between questions to which answers are known and those to which answers are yet to be obtained, and may deprecate the role of the teacher. Beyond this, students gradually develop an appreciation of the importance of argument and substantiation and the need to make their own decisions.

According to this model the transition from dualism to multiplism is associated with a decline in the certainty with which knowledge is viewed, followed by a gradual regrowth in certainty as a commitment to relativism develops (Figure 1). This view has natural correlations with Piaget's developmental model, according to which students at the concrete operations stage are able to classify concepts, but are unable to operate on those groups, an ability that is associated with the formal

operations stage [24]. Both models involve a sequence of stages through which a student progresses by interaction with the environment. Despite this apparent similarity, Perry *et al.* [32] concluded, on the basis of a very small number of students, that the two models describe fundamentally different aspects of intellectual development.



**Figure 1.** Summary of the approximate development of the certainty of knowledge (smooth curve) and the Perry scale (adapted from [14]), showing the approximate position of the Piagetian concrete-formal operations transition (dashed line) based on the data obtained by Perry *et al.* [32].

A significant proportion of students at the interface of secondary and tertiary education think dualistically [14, 32] and are at the concrete operations stage [10, 20, 41]. For example, Perry *et al.* [32] assessed a small number of graduate and undergraduate university students according to these two models. Despite being specifically selected to represent a range of Perry positions, 97% of the students were at the concrete operations stage and 78% of those students had characteristics associated with Perry’s position 2 or 3 (Figure 1). Naturally, individual students may operate across a range of positions depending on the nature of the task, but, based on Perry *et al.*’s [32] data, the decline in certainty associated with progression through Perry positions 2 and 3 and the subsequent rise from position 4 onwards correlates with the decline in concrete operations and the rise in formal operations (Figure 1). Beyond this is higher order thinking that is infrequently encountered among students.

One consequence of the cognitive development of late secondary and early tertiary students is that they can apply particular rules, but fail to understand them [2, 10, 20]. For example, many students struggle to understand the concept of molarity [16]. They often recite ‘ $c_1V_1 = c_2V_2$ ’, an expression of the conservation of the number of moles of a solute when a solution of concentration  $c_1$  is diluted to concentration  $c_2$  by changing the volume of a solution from  $V_1$  to  $V_2$ . While they may be able to apply this expression in simple circumstances, very few of them appreciate the underlying significance. This is inevitable since the same students often fail to recall that concentration ( $c$ ) is just the number of moles ( $n$ ) in a specific volume ( $V$ ) – essentially the density of molecules in solution ( $c = n/V$ ), since a mole is just Avogadro’s number ( $\approx 6.023 \times 10^{23} \text{ mol}^{-1}$ ) of molecules. As Herron [20] points out, many students struggle with any concept involving ratios, as both molarity and dilution do, so it is hardly surprising that these are challenging to students.

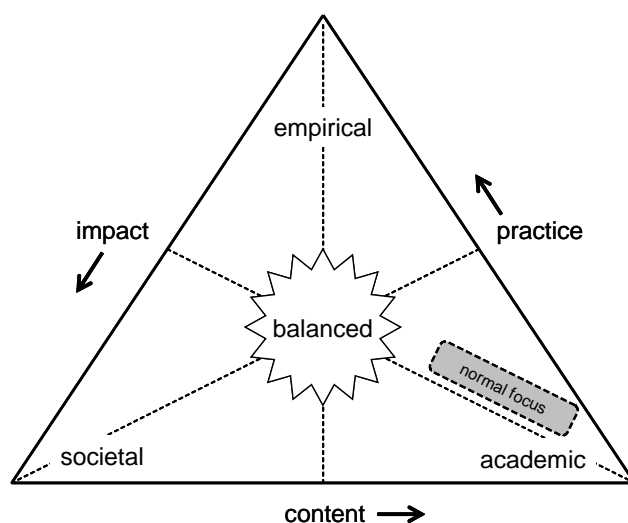
Such errors indicate a failure to appreciate basic technical concepts and illustrate an important difference between student and teacher: students tend not to think about their own thinking, a characteristic of formal thought [24]. They do not appreciate that the errors they make are “...

interesting, because they reveal a thought process and, by contrast, shed light on some structural features of accepted theory. The stumbling blocks in common reasoning point to certain aspects of theory on which particular stress should be laid” [42]. Such metacognitive activity is a significant aspect of critical thinking and of the practice of science. With experience comes the realisation that “[p]edantry can be the enemy of insight” [40], but that one must be able to judge the amount of rigour appropriate to the circumstances. Practising scientists actively search for points of incomprehension and inconsistency, and science teachers also strive to discover what it is that students do not understand, among much else.

Students at different Perry positions have different needs and, it has been argued, will be unable to comprehend an approach focused even two positions higher or will be bored by an approach aimed at lower positions. An understanding of the cognitive development of the students must, therefore, inform both the content selected by and the approach and expectations of the teacher.

#### 4. Developing critical thinking skills in students

Critical thinking involves a wide range of skills, such as obtaining and evaluating information, analysing data and developing questions. If students are to develop such skills, they need to be emphasised, valued and modelled by teachers. Science literacy involves a combination of content knowledge, an understanding of the practice of science and an appreciation of the impact of science (Figure 2, [31]). In most classrooms the focus is on content rather than being more balanced [35].



**Figure 2.** Balance of the components of science literacy [31] in education. The dashed lines are intended to simply guide the eye. The ‘balanced’ zone indicates the position where the three forms of science literacy are roughly similarly weighted and the grey zone indicates the approximate balance of most science education. The extremes of focus on content, science practice and impact are indicated by ‘academic’, ‘empirical’ and ‘societal’, respectively.

The first step in developing critical thinking skills is simply to refrain from educating the questioning attitude out of students. In some respects, children can be much better scientists than young adults that have undergone several years of science teaching [26]. Children are comfortable asking questions, whereas older students are more wary and generally appear to have developed the idea that there is always an answer (a dualist position) and that they should probably know what it is. The ability to question and imagine is not often cultivated in science classrooms. The focus on teaching and learning is associated with a tendency to concentrate less on thinking. This is reflected in textbooks, which often fail to encourage deep thinking [18, 36, 37].

Having refrained from discouraging questioning, the next step is *actively* to encourage questioning, which inevitably means that students develop skills in formulating questions of various types [7] and identifying a lack of comprehension or clarity. Moreover, it is important to cope sensitively with students who do not “know ‘the’ answer”. So ingrained in students is the idea that they ‘should’ have an answer, that they are actually deterred from questioning, thereby reinforcing the natural reluctance of most students to expose ignorance or risk being thought ‘stupid’. Overcoming this reluctance requires an environment in which every question is considered constructively and without judgement, while clearly identifying what is reasonable [6]. I point out to my own students that textbooks are replete with ‘misconceptions’ that may or may not have been erroneous at the time of printing; that today’s ‘knowledge’ is, potentially, tomorrow’s ‘misconception’; and that “... ignorance more frequently begets confidence than does knowledge” [12]. While this usually applies to details, there are examples of large scale theoretical revisions (such as the replacement of squiggle~P with the chemiosmotic hypothesis [38]). Textbook ‘errors’ and student ‘misconceptions’ should be considered in the light of this potential for revision, moreover, each teacher has her or his own selection.

By developing and using questioning skills, the teacher both models the approaches of a scientist and helps students to construct their own practice. In this respect, the teacher demonstrates how science is done before any experiment is even contemplated. In science the teacher usually provides answers, in contrast with some other disciplines in which a stance of ‘not knowing’ is natural [3], but this may not assist the student to see how to cope with the challenge of new ideas. For some years I have employed a strategy of claiming not to be able to answer questions and then engaging the class in a group analysis of the problem [6]. This has several benefits: (i) it implicitly gives the students permission to admit publically to not knowing; (ii) it models appropriate responses in a situation in which one is uncertain; (iii) it allows the students to observe how the exploration of the known to analyse the unknown, thereby modelling the behaviour of a scientist; (iv) it enables the teacher to model questioning skills and for the students to practise them; and (v) places the ‘burden’ of analysis, without responsibility, on the students. This approach is collaborative, but the teacher must take care that the students eventually appreciate the desired concepts.

Critical thinking requires practice and some strategies that can be augmented with experience. For example, humour can be valuable [17]: it helps to relax students, reinforces the relationship between student and teacher, and can make specific points more memorable. I sometimes suggest ‘silly’ answers to try to elicit a less constrained response; implicitly, students then have ‘permission’ to say what is on her or his mind, no matter how ‘silly’ the student might think it to be. This usually elicits laughter, followed by a response that enables me better to understand the student’s position on the concept being considered. This ‘freedom’ from constraint is a necessary part of critical thinking, so in following this path I intend to model a technique for liberating the mind from dualistic thinking so common among students. Essential to this approach is that the teacher is non-judgemental: contributions are welcomed, no matter how bizarre, but eventually some clarity as to what is most reasonable must be established. The mental relaxation is temporary, because whatever arises during that phase must then be analysed.

Critical thinking is intrinsic to the practice of science, but, other than the ‘scientific method’, it is little emphasised in most classrooms. Instead, the focus is usually on content (Figure 2). It has been argued that “... shifting the fixation from the content of science to the activity, experience and presuppositions of science ...” [11] would assist in making science more accessible. In parallel with the rapid growth of science in recent decades there has been a shift in teaching away from the fundamentals underlying all science towards higher level material. For example, secondary students are often taught about the polymerase chain reaction (PCR, [5, 23]), but they have little conception of its physicochemical basis, which may be unsurprising given their cognitive development. In this case, as in many others, an understanding of the underlying concepts empowers the student to be able to work independently on more than just the PCR mechanism. This is one aspect of what Bruner [8] meant by “... leaping over a barrier.” By emphasising high level concepts (such as PCR), fundamental concepts are de-emphasised and students tend to try to remember ‘answers’ rather than think problems through for themselves. Students learn the specific rather than the generic, which leads to a lack of the technical knowledge required to apply and develop critical thinking.

Scientists intend their statements to be precise, to express so much and no more, but it is inevitable that some ambiguity is introduced by the language used. Bertrand Russell [39] wrote that “[o]rdinary language is totally unsuited for expressing what physics really asserts, since the words of everyday life are not sufficiently abstract. Only mathematics and mathematical logic can say as little as the physicist means to say. As soon as he translates his symbols into words, he inevitably says something much too concrete, and gives his readers a cheerful impression of something imaginable and intelligible, which is much more pleasant and everyday than what he is trying to convey.” Students get used to dealing with high level concepts rather than the precise statements on which those concepts are based. In part this is because the fundamental concepts are thought to be too ‘dry’, but, for example, elegant and exciting as PCR may be, learning about the reaction does less to promote critical thinking and an appreciation of the practice and nature of science than Faraday’s [13] superficially simple observations of a candle. His precise observations and statements, requiring surprisingly little knowledge, yield extraordinary insight based on developing critical thinking.

Systematic practice, guidance and encouragement are necessary to develop critical thinking skills. In addition, the questioning attitude of students must be nurtured, ‘error’ should be treated as a chance to investigate and learning should be based on understanding rather than memorisation. Little of this is novel, but even those who believe that they focus on critical thinking may not actually do so [18]. Each teacher should model the appropriate behaviour and approaches, which means that those same skills have to be even more highly developed in the teacher.

## 5. Critical thinking in teaching

In essence, the teacher models the behaviour of a scientist: promoting questioning at all levels and careful analysis of the issues. Consequently, each teacher should endeavour to develop the necessary skills so that the students’ difficulties can be appreciated and a clear demonstration of critical thinking can be achieved. This takes time, effort, practice and, especially, a willingness to acknowledge one’s own ignorance. In so doing, the teacher will inevitably strengthen his or her own ability to identify a lack of understanding in students. Moreover, a focus on clarity of thought, observation, analysis and reasoning, combined with a willingness to work on fundamental concepts, will enhance the success of both teacher and student. Naturally, both the cognitive development of the students and their pre-existing knowledge need to be understood by the teacher and an appropriate approach developed.

The issues for teachers of science are (i) what the necessary skills might be, (ii) how they can be developed in (a) their students and (b) themselves; (iii) how these skills might inform their teaching; and (iv) what attitude towards science might be desirable in a scientifically literate person. The skills include an ability to obtain and organise information of various sorts; identify an absence of knowledge or understanding; identify and weigh the relevant evidence; design experiments and analyse the results obtained; apply pre-existing ideas; and generate new ideas. Each of these (and others) is more or less important depending on the circumstances.

## 6. Conclusion

Science teaching, like science, is not simply the revelation of a static catalogue of knowledge. An appreciation of the practice and impact of science helps to develop science literacy and renders the content useful, useable and relevant. One of the most important tools of the scientist and the science teacher is the ability to formulate questions, which relies on sustained critical thinking based on a growing body of knowledge. The development of this attitude requires practice in a classroom environment in which questioning is valued, encouraged and appreciated; in which ‘errors’ are seen as an opportunity to explore; and in which being able to think is valued more than simply remembering. In short, science should happen in the classroom if it is to be seen to be relevant to life outside the classroom.

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