A case for some uncertainty in science education
Un caso de incertidumbre en la educación en ciencias

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Abstract

This paper will exemplify data from both formal and informal research that demonstrate the range of alternative understandings in very basic science. The author has his own alternative understandings. This raises issues of the certainty and constancy of 'right answers'. The author is convinced (almost certain) that uncertainty is an essential and currently undervalued dimension in Science Education. Accepting uncertainties inherent in authoritative statements and the various interpretations by students and teachers demands a continuing critical re-examination of meaning. It is argued that an appropriate level of uncertainty facilitates students' engagement in learning and brings 'learning science' much closer to real practice of 'doing science'. There remains an important question of balance and how we gain both acceptance and valuation of wondering, questioning and doubting by all concerned with the learning and teaching of science. Beyond the classroom it is now clear that science itself and as applied to the real world of complex systems such as the environment, the atmosphere or the brain is inherently uncertain. Surely science education must reflect some of this uncertainty if there is to be a chance that the general public can be sensibly engaged in the serious scientific and technological debate and decisions that face mankind in forthcoming decades.

Key words: *science education, wondering, uncertainty*

Resumen

Este trabajo muestra los datos de una investigación formal e informal sobre el rango de comprensiones alternativas en la ciencia básica. El autor tiene sus propias comprensiones alternativas. Esto levanta problemas de la certeza y constancia de "respuestas correctas". El autor se convence (casi cierto) que esa incertidumbre es esencial y que actualmente casi no se tiene en cuenta en la educación en ciencias. Las incertidumbres inherentes en las declaraciones autoritarias y las varias interpretaciones por los estudiantes y los maestros requieren una constante reexaminación crítica del significado. Parece que un nivel apropiado de incertidumbre facilita el compromiso de los estudiantes de aprender y acercar este aprendizaje de la ciencia a la práctica real de 'hacer la ciencia'. También existe una pregunta importante de equilibrio y cómo ganamos aceptación, valoración de las maravillas de la ciencia, cuestionando y dudando sobre todo lo relacionado con el aprendizaje y la enseñanza de la ciencia. Más allá del aula está claro, que la ciencia y sus aplicaciones en el mundo real de sistemas complejos como el ambiente, la atmósfera o el cerebro, es inherentemente incierto. Ciertamente la educación en ciencias debe reflejar alguna de estas incertidumbres para que el público en general tenga la oportunidad de acercarse al debate científico y tecnológico serio y a las decisiones que debe enfrentar la humanidad en las décadas venideras.

Palabras clave: educación en ciencias, maravillas de la ciencia, incertidumbre.

INTRODUCTION

This paper has developed from a presentation given earlier that related to teachers' continuing learning of chemistry and the implications for science teaching (GOODWIN, 2001b). In the presentation a number of instances of teachers' learning were explored. These were taken from a personal perspective and from evidence collected during more formal research. One of my conclusions was that, as a consequence of fallibility, incompleteness or misunderstanding *any* knowledge transmitted from an authority to a learner is inevitably uncertain to some extent. It is therefore necessary for both learners and teachers to continually and critically appraise their own understandings and, where possible, *negotiate* meanings together.

'Learning through teaching' is an experience common to all who have ever tried to teach. (I should say 'almost all' since there is uncertainty here too. Indeed, two chemistry teachers who returned a questionnaire to me answered 'Not applicable' to a question asking them to exemplify their learning as teachers!) Mostly, science teachers are only too ready in informal discussion to attest to the fact that their understanding of science has developed considerably during the processes of preparing to teach and of teaching.

All this seems relatively unproblematic, and perhaps even trivial, until it is placed within a context of governmental, public and (sometimes) student expectations of their teachers. In the UK we have had a national curriculum for schools only since 1988 (details of current specifications for all subjects and levels are readily available on the Internet.) and PAUL BLACK (1995) published a perceptive account of the process of implementation. More recently standards for initial teacher training have been published (DfEE, 1998) which included *inter alia* a twelve page list of science skills and concepts that must be understood by all intending primary school teachers *before* they are allowed to qualify. Most of these students have studied no formal science since they passed their own 16+ examinations. A science pass at this level is an entry requirement for initial teacher training courses. As an agenda for learning the DfEE – Department for education and Employment (now DfES - Department for Education and Skills) list is useful, but as a tandards the items were absurd. The list was particularly problematic for those of us engaged in teacher education, who are still learning and wish to explore the meanings and significance of many of the items on the list. The latest set of professional standards (2002) no longer contains this list 'merely' requiring that "newly qualified teachers be *confident and authoritative* in the subjects they teach…".

There has always been an expectation that teachers should 'know their subjects' and in no way should this paper be interpreted as lessening this imperative. However, it is not possible that anyone should 'know it all' and in the presentation referred to (GOODWIN, 2001b) four sources of uncertainty in even the most carefully prepared lessons are identified:

- The authority from which the material was originally learned or the texts referred to may have become outdated or been in error.
- We may be so sure that we are right that no need is perceived to make any further checks. (Without *considerable* confidence in our knowledge it would never be possible to teach, write books or actually do science at all).
- We may be making the unwarranted assumption that the words we use have the same meanings for our students.
- We may not have anticipated questions that arise *as a consequence* of teaching. For example, new personal insights or questions from even more insightful students may be an outcome of the teaching. In these cases, learning by the teacher *must follow* the teaching.

In this paper these ideas will be taken further and the following will be tentatively explored:

a A typology of uncertainties that can be exemplified within science education.
b A variety of science education contexts in which uncertainty seems currently to be less acceptable.
c The possible values of uncertainty in science and education.

The paper will conclude with suggestions of consequences for science teaching.

A. A TYPOLOGY OF UNCERTAINTIES:

(Note: The estimation of limits of possible error and uncertainty is an important aspect of doing quantitative science. This, however, is not a major focus in this paper).

1. The meaning and understanding of words (and other signs and symbols).

The meanings carried by words are constructed by individual users and inevitably vary with the experience and level and sophistication of the users. Some words (e.g. work, power, chemical change.) have very particular meanings in a scientific context. However, just because words are carefully defined does *not* mean that people, even scientists always use them appropriately. The words 'atom' and 'molecule' for example are used differently (and correctly?) by scientists depending on whether they are considering elements combining together or 'simply' discussing states of matter in terms of the kinetic theory. For most students and the general public an atom is something very small but, for many, it is also something dangerously explosive and to be avoided at all costs!

In a recent paper (GOODWIN, 2002) the author had the temerity to suggest that it *might* be harmful for future learning if teachers were too sure that it is wrong to say that salt melts when it dissolves in water. Clearly one reviewer of the manuscript was very upset:

> "One of the obstacles to science learning at any level is that students arrive saturated with misinformation and sloppy reasoning skills; the challenge of science educators is to develop patterns of careful thinking. Not only do I NOT believe that careful terminology at the elementary school will 'constitute a barrier to subsequent chemistry learning', but I consider it the obligation of teachers to impart to their students valid science unsullied by the 'fuzziness' of everyday speech".

Some violent disagreements from some chemists to an earlier suggestion that fizzing drinks are, in fact, *boiling* solutions (GOODWIN, 2001a) have also been received. A narrow majority of correspondents seems to agree with me that fizzing drinks are boiling, but the debate is far from being closed.

2. The interpretation of models and the distinction from reality

This is a common issue for teachers and learners of science – the reality, identity and nature of an electron, for example all cause problems. Electrons are often drawn on diagrams, labelled, described as 'belonging' to one atom or another or behaving as waves or particles. Most scientists seem to believe in electrons occupying 'orbitals' within atoms and molecules. However, how close our individual models are to each other, or to 'reality', is a matter for continuing philosophical debate. (The •or ^{x} often used to designate sodium or chlorine electrons when showing the formation of sodium chloride *seem* to imply that the electrons are different in sodium and chlorine atoms! Perhaps the latter are green?).

3. Classifications

In science teaching the classification of things or processes into specific categories is often useful. The allocation of 'everything' to a particular category is, however often over stressed and students are left looking for a 'right' answer when the categorization is not clear and unlikely to be useful. An example would include the distinction between chemical and physical changes. There would probably be no argument that the action between sodium and water is properly classified as a chemical change. But, what about the dilution of concentrated sulfuric acid with water or the solution of common salt in water. The author would *now* argue that the former is definitely a chemical change and that the latter *probably* is too. It really depends on whether hydrated sodium and chloride ions are considered to be *chemically* distinct from anhydrous ones. (However, in the early stages of chemistry learning, when covalent acids and ionic salts are in the future both these changes might more 'correctly'/'usefully' be designated as *physical*?)

I thought that the classification of many substances into solid, liquid and gas states was unproblematic until another chemist in correspondence about salt 'melting' in water made the comment to me that:

> *"When salt dissolves in water it forms a solution, but the salt **does not enter the liquid state**".*

Subsequent discussion elicited the belief that the salt was now in the 'ionic state'.

4. Application of rules, laws and generalizations

These clearly link to understandings of words and classifications. However, a specific example was my surprise that two thirds of a sample of 52 science graduates believed that the temperature of a liquid does not change when the liquid is allowed to evaporate (GOODWIN, 2001b; 2003). It appears that many of them have learned and applied uncritically the rule that 'the temperature and state of a substance do not change at the same time'. (The state is changing therefore the temperature must remain the same.) The rule is 'true' for changes at the melting or boiling points of pure substances, but in general it is false.

In the context of this paper mention, at least, must be made of the Heisenberg Uncertainty Principle!

5. Inappropriate Explanations

On occasion an explanation for a particular phenomenon may be 'so obviously plausible' that it must be correct. A case in point is the explanation as to why the shaking of a can of Coke immediately before opening has such a major – explosive - effect when the ring is pulled. Clearly the energy imparted by shaking causes a temperature rise, which causes a pressure rise (carbon dioxide is less soluble in hot water)? In 'fact' the change in pressure due to shaking must be miniscule (DEAMER and SELINGER, 1988, GOODWIN, 2001a) and the explanation 'must be' in terms of the kinetic effect of distributing small bubbles throughout the liquid.

6. Error and inconsistency

Scientists and science teachers are human and, especially when caught off guard, do not always use even the most basic scientific concepts and vocabulary with complete consistency. What science teacher, however keen s/he is on a proper distinction between mass and weight often asks pupils to hang weights (rather than masses) on a spring, and will rarely measure his/her own weight in Newton's. Also, Newton's laws tell us that no force is required to keep an object moving with constant speed in a straight line. How many of us really think in these terms when walking or riding a bicycle?

7. Classroom uncertainties.

Even if we assume a well-ordered situation with motivated students so that deliberate disruption or sabotage can be discounted uncertainties would include the following:

a. Lack of clarity of teacher instructions

b. Misunderstanding or lack of concentration from students

c. Measurement errors

d. Lack of skill

e. Mathematical incompetence

f. Too much or too little 'cognitive demand'

B. CONTEXTS IN WHICH UNCERTAINTY SEEMS UNACCEPTABLE:

1. In teachers' knowledge

This is frequently the interpretation of 'national standards' or guidelines for school inspectors. Teachers feel under pressure to 'get it right' and to be able to answer all their students' questions.

There is no argument that good teachers know their subjects and can deal confidently with subject skills and knowledge at a level appropriate for most of their students. However, it is also important that they can contend effectively with and value other plausible alternative conceptions that are sincerely held by their students. It may be that on occasions students' perceptions will challenge or even change the teacher's own conceptions. (If and when this happens, and the student is aware of it – it can be a fantastic boost to the students' own self esteem and the teacher does not need to 'lose face'.)

2. In testing and examinations - especially objective testing

Here it seems that 'right answers rule'.

The major dangers seem to be when it is assumed or implied that:

a. Testing covers everything that is worthwhile about performance in the subject. (i.e. the test is totally valid)

b. That the test can be marked with total reliability (and reproducibility). Can we really be assured that 55% is 'better' than 54%? Test results usually contain sufficient uncertainty that it would be unsafe to differentiate between candidates on the basis of these scores.

This can be particularly problematic when really significant decisions rest on the result of a particular test.

A focus on the importance of test scores may lead some students to attempt to learn 'right answers' rather than develop a meaningful grasp of the subject. The situation is doubly dangerous to educational 'standards' if the teacher also is *only* concerned to maximize the students' test scores. This may occur, for example, if it is felt that career progression, professional standing or the schools' 'quality' is to be judged mainly on student performance on such measures.

3. Subject 'experts'

Some such 'experts' may try to insist that everyone maintains the same 'standards' that they are usually able to employ themselves. Their disdain for the sloppy thinking of others and their lack of forgiveness even for students trying their hardest can be dispiriting. (They are themselves severely 'at risk' should they be 'caught out' making a careless error.)

4. Politicians and Journalists

Unfortunately, politicians need simple straightforward answers and policies that can be uttered through a series of slogans and sound bites. Complexity and uncertainty get in the way of short term and large-scale actions. When the actions turn out to be wrong it is someone else's fault. Similarly, journalists need a simple message and often build in certainty into their headlines by omitting the limitations of research - and the reservations of the researcher. In any case if it is not 'world shattering' or linked to a celebrity - it's not news.

C. VALUING UNCERTAINTY:

It is fairly recently that the author has begun to see too much certainty as a 'bad thing'. However, it seems that there are many others accept and even celebrate uncertainty. Some examples will hopefully illuminate this point from a number of different perspectives:

- *"It is actually healthier to be slightly unsure about meaning - and thus aware of our uncertainty - than it is to take it for granted."* (WONG, 2001)
- *"I feel a responsibility to proclaim the value of this freedom to teach that doubt is not to be feared, but is to be welcomed as the possibility of a new potential for human beings. If you know you are not sure you have a chance to improve the situation. I want to demand this freedom for future generations. p. 28.* (FEYNMAN (1963) - published 1998.)
- *"People say to me, 'Well, how can you teach your children what is right or wrong if you don't know?' Because I'm pretty sure of what is right and wrong. I'm not absolutely sure; some experiences may change my mind. But I know what I would expect to teach them. But, of course a child won't learn what you teach him." p. 67.* (FEYNMANN, ibid).
- *"Most peoples' encounter with science in primary school, secondary school and even in universities, is through courses that teach stuff that scientists (think they*) thoroughly know. So most peoples' encounter with science is as a set of things we (think we*) really understand, whereas, of course the really interesting problems tend often to arise when we are beyond the frontier and we don't understand. All the areas of dispute and excitement and worry are in the relatively small, but disproportionately important areas where we do not really understand things yet. For that, the intuition shaped by what you do in school is inappropriate". pp. 28-29.* (EVANS, 2000). (Sir Robert May was the Government Chief Scientific adviser).
(* My additions)
- *"In a particularly telling example, Peat describes the everyday traumas facing anyone trying to make eco-friendly decisions. Again science has taught us that issues of environmental impact are replete with uncertainties, from life-cycle costs to ecological feed-back loops. Yet, while we know this to be true, we still cling to the old view that there must be one 'right' answer while all the others are 'wrong'. (MATTHEWS, 2002)*
- *"It is terribly important not to become too concrete".* (When trying to characterise 'autism'.) (HOBSON, 2002)
- *"But they understood each-other perfectly. They were both men whom childhood had abandoned without trace. Men without curiosity. Without doubt. Both in their own way terrifyingly adult. They looked out at the world and never wondered how it worked, because they knew.* ***They*** *worked it." p. 248.* (ROY, 1998).

The last reference is well outside any science education context, but it does seem to indicate the terrifying possibilities of absolute certainty.

From a science teaching perspective it is not difficult to find examples of 'facts' (or things that I now believe to be true - that at some time in the past I am conscious of having believed and probably 'taught' the converse.) Some of these are listed below, but, of course, it may be that *you* knew the truth all along?

- Some hydro-electric power (HEP) stations produce more polluting gases (methane and carbon dioxide) per kilowatt hour of power than some coal fired power stations. I believed HEP to be virtually pollution free in operation.
- It takes millions of years for a photon of light to get from the center of our Sun to the outside edge. Since light takes only eight minutes from leaving the Sun to reaching the Earth I had assumed the time to the edge of the Sun would be much less than a minute.
- When an electric current is passed through a solution of hydrogen chloride in water most of the current is carried by the hydrogen ions. I certainly implied in my teaching, that equal amounts would be carried be the hydrogen and chloride ions, since equal numbers of each ion *are* discharged at the respective electrodes.
- That *fizzing* drinks are *not* boiling and that the pressure inside a can of Coke *does* increase when the can is shaken vigorously.

D. CONCLUSIONS:

Too much uncertainty would clearly reflect adversely on perceptions of teacher competence and confidence of all concerned. However, in the past science teachers and scientists have laid immense value on certainty. It now seems clear that to be effective and useful in the 'real life' worlds of technology, conservation, environment and other global concerns science and education in science need to embrace an *appropriate* amount of uncertainty. A possible strategy is indicated in Matthews' (2002) review:

'Peat suggests that we might adopt one of Nature's preferred strategies, and encourage diversity in both thought and action wherever possible. A strategy that has served Nature well enough for a few billion years would seem as good as any'.

Of course, this was aimed at science rather than science education, but at a time when we are focusing on 'subject standards' it may be that we have underemphasized the flexibility, variety and wonder required to engage students (and teachers) in learning science. In reality the human condition on our small planet is terribly complex and ultimately uncertain.

The relatively predictable and easily examinable (although, not necessarily 'common sense' or easily understood) basic science that forms much of the school curriculum is important, but the contexts in which it is really applied are essentially complex and uncertain. Links to this uncertainty must be made especially when in real life; ethical, moral, economic, religious and cultural dimensions enter the equation. Just because something is known or can be done does not mean that it *should* be done or, even if it is desirable, that it has priority over other desirable actions. Even in the less contentious aspects of basic science *some uncertainty* gives room for improvement. It legitimizes each student's intellectual engagement with his/her own ideas and those being promoted by the teacher. It requires them to seek out, to examine and to evaluate evidence – and to question authority. It promotes debate with peers and teachers. Overall it gives *learning* precedence over *knowing.* Less certainty would, almost certainly, would be more educational for all engaged in the learning and teaching of science.

BIBLIOGRAPHY

BLACK, P., "1987 to 1995 - The Struggle to Formulate a National Curriculum for Science in England and Wales." *Studies in Science Education,* 26, 159-188, 1995.

DEAMER, D. W. and SELINGER, B. K., "Will that pop bottle really go pop? An equilibrium question" *J. Chem. Ed.,* 65 (6) 518, 1988.

DfEE, "Teaching: High Status, High Standards - Requirements for Courses of Initial Teacher Training." *Circular Number 4/98,* London. (Available on line at http://www.dfee.gov.uk/circulars/4_98/summary.htm (Accessed July 2002), 1998.

EVANS, J., No beating about the bush - an interview with Sir Robert May. *Chemistry in Britain* 36 (10) 28-30, 2000.

FEYNMAN, R. P., Published 1998. *The Meaning of It All; Thoughts of a Citizen-Scientist.* Reading, Massachusetts, Addison-Wesley 1963.

GOODWIN, A. (2001a) 'Fizzing Drinks, are they boiling?' *Journal of Chemical Education* 78 (3) 385-387.

GOODWIN, A. (2001b) The Chemical Education Research Group Lecture, Royal Society of Chemistry, "*Teachers' Continuing Learning of Chemistry: implications for pedagogy.*" Variety in Chemical Education Conference, Lancaster University. (Sept.) This CERG Lecture No 4 can be viewed at: http://www.rsc.org/lap/rsccom/dab/educ002.htm (Accessed July 2002.)

GOODWIN, A., 'Is Salt Melting When It Dissolves in Water' *Journal of Chemical Education,* 79 (3) 393-396, 2002.

GOODWIN, A., 'Evaporation and Boiling - beginning graduate science teachers' understandings.' *School Science Review,* 84 (309) 131-141, 2003.

Hobson, P., In an interview with Liz Else, reported in *New Scientist* No 2351, 13th July, p. 46, 2002.

MATTHEWS, R., 'The way it sort of is' a review of '*From Certainty to Uncertainty'* by Peat F D, in *New Scientist* No. 2345 1st June, p. 54, 2002.

ROY, A., *The god of small things; a novel.* New York, Harper Perennial, 1998.

WONG, D., Editorial *J. Res. Sci. Teaching,* 38 (3) p. 280, 2001.

Note: This paper was presented at the Annual Conference of the Association of Tutors in Science Education (ATSE) at the University of the West of England in August 2002. An earlier version was given to the 17th Biennial Conference on Chemical Education held at the University of Western Washington, Bellingham WA, USA in July 2002. The author is not certain that the paper is fully developed and comments and constructive criticism would be most welcome.

Received 29.09.2003, approved 05.03.2004