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The Place of Analogies in Science Education

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ABSTRACT *The role of analogy in learning has been extensively researched in science education. The core purpose of the use of analogy as a strategy deployed in teaching is that of developing understanding of abstract phenomena from concrete reference. Whilst such an objective is desirable, it is predicated on the assumption that there is an agreed interpretation of the particular phenomena under scrutiny to which all subscribe. This paper argues that such a position is untenable and that the research enterprise should shift focus from determining the effectiveness of analogy in cognitive transfer from base to target domains towards the recognition of the role of analogy in generating engagement in the learning process. In such a paradigm, meaning in science for both learner and teacher is derived from discourse rather than being independent of it. The discussion draws on hermeneutic philosophy to provide a theoretical framework to illustrate the implications for teacher subject and pedagogical knowledge.*

INTRODUCTION

The role of analogy in learning has been extensively researched in science education. The core purpose of the use of analogy as a strategy deployed in teaching is that of developing an understanding of abstract phenomena from concrete reference. Whilst such an objective is desirable, it is predicated on the assumption that there is an agreed interpretation of the particular phenomena under scrutiny to which all subscribe. I shall argue that such a position is untenable and that the research enterprise should shift focus from determining the effectiveness of analogy in cognitive transfer from base to target domains towards the recognition of the role of analogy in generating engagement in the learning process. In such a paradigm, meaning in science for both learner and teacher is derived from discourse rather than being independent of it.

The use of analogy in developing understanding of phenomena is not restricted to science education. Dreistadt (1968) catalogues the central role of analogies in the history of scientific ideas, including the works of Einstein, Darwin, Bohr, Mendeleev and Kekule. This is not entirely a surprise, since explanation of the abstract needs to be rooted in existing experience in order to interpret increasingly sophisticated ideas. In reasoning through analogy the scientist in the scientific endeavour and the student and teacher in science education are involved in the same process. Developing meaningful explanation

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could therefore be considered the core enterprise of both scientific endeavour as well as personal learning in science. That this is the principal task in pedagogy is supported by the plethora of research literature focused on learners' misconceptions across a wide range of conceptual domains (Pfundt & Duit, 1994).

SCIENCE AND MEANING

The complexity of the pedagogical challenge in this regard concerns the unnatural nature of scientific explanations of the world that conflict with life-world experience (Wolpert, 1992). Intuitive notions of phenomena such as forces, energy, seasons and electric circuits are seldom congruent with scientific explanation. Science seems incompatible with life-world experience. These scientific explanations constitute *the text* (Eger, 1992) of science that both teacher and student encounter in science education discourse, the parameters of which are traditionally considered as being defined by textbooks, curriculum syllabi and, to a lesser extent, in school science at least, research.

The problem that both teacher and student face with regard to this text is that of interpretation such that scientific explanations are underpinned with causal mechanisms that are meaningful and coherent. This could be considered the underlying rationale for the teaching through analogy of abstract phenomena such as electricity in order that the learner can develop causal mechanisms to explain the behaviour of simple circuits. However, within this enterprise there is implicit the notion that science text is somehow given *a priori* and stands independent of discourse in science learning and teaching. The conspicuous absence of what constitutes the scientifically acceptable in the misconceptions literature in science education seems to underline this view. In the following discussion I shall argue that such an epistemological position requires further scrutiny.

INTERPRETATION AND HERMENEUTICS

It is with regard to the focus on meaning from the interpretation of text in science learning and teaching that the appropriation of the discipline hermeneutics emerges, the modern origins of which evolved from the interpretation of biblical texts at the turn of the 19th century. This has been recently illustrated, for example, through the work of Gallagher (1992), who has developed a comprehensive account of the application of hermeneutic principles to education, and Eger (1992, 1993a,b), who provides a detailed examination of the philosophical issues concerning the appropriation of hermeneutic inquiry to both science and science education. The practical implications of this work for the development of teacher subject and pedagogical knowledge in science has also been explored (Heywood, 2000) and the potential for further inquiry, whilst contentious, does offer the opportunity to contend some of the taken for granted assumptions on which some science education research is based. Whist it is not possible to deal with the principles of hermeneutics in depth, for the purposes of this discussion I shall attempt to underline its relevance in terms of the nature of scientific explanation and, more importantly, how this can be presented in science education.

A central tenet of hermeneutic inquiry is that of undecidability in which the absolute meaning of a text is deferred because there always remains the possibility of alternative interpretation. This sits uneasily with a conceptualisation of science as knowledge of how things are, in which it is argued that the issue of decidability is critical to the scientific endeavour, whereby competing theories are decided upon the basis of empirical evidence. (The mechanisms underpinning the 'method' of inquiry in respect of this have been the central focus of 20th century debate in the philosophy of science; see for example Popper, 1963; Kuhn, 1970.) This has had a pervasive influence on the presentation of science knowledge in the curriculum, such that knowing is privileged over understanding, practical inquiry over discourse and method over interpretation.

THE NATURE OF KNOWING IN SCIENCE

There arises from this a significant issue that is seldom recognised in science education research literature on subject and pedagogical knowledge concerning the perception as to where meaning resides. Hermeneutics challenges the notion that *meanings* await expression independent of the language used to describe them (Brown, 1997) and I shall offer two examples to illustrate the point. First, take the idea of fields that evolved from the work of Faraday on electricity and magnetism, a comprehensive historical treatment of which is given by Gooding (1989). Faraday initially developed the concept from meticulous experimental procedures including the observed effect of magnets on iron filing patterns. Subsequently, these effects were eventually interpreted as evidence for the existence of a field of force exerting influence on matter. The field description (i.e. the language of fields) which had derived from observed magnetic effects then evolved an independent ontology through Faraday's interpreted *reconstruction*.

> The process of reconstruction makes natural phenomena—which have been accessible *only through human construction and intervention*—come to be accepted as *independent* of that activity. The residue of phenomena thus came to appear as objects *independent of human intervention* [my emphasis]. (Gooding, 1989, p. 216)

The reading of natural phenomena then comes about through the human act of interpretation. Historically, the idea of fields developed into a generic concept useful in describing a diverse range of physical phenomena (the electromagnetic field). The abstraction has since become increasingly remote from concrete models and analogous reasoning such that the epistemology of science as an ontological reading of how things are is derived from abstracted interpretation *in language*. In learning science this requires an integration of interpretation, the difficulty of which should not be underestimated. The physicist Feynman (1965) acknowledged that conceptualising the abstract notion of fields in concrete analogous terms was a pointless endeavour because there exists no analogous equivalent.

As a second example, consider the abstraction of ideas concerning waves derived from concrete experience analogous to water. This paradigm has progressed from the concrete visualisation that parallels wave behaviour in a recognisable medium (in this case water) towards abstract mathematical models. Along the course of this historical development of wave theory the medium through which electromagnetic waves travel (the ether) was discarded, leaving only the waves themselves, a metaphysical position which has no analogous equivalent. In this there emerges an apparently absurd notion, that of describing the behaviour of waves in a pond whilst maintaining at the same time that the pond has no water. However, it is these descriptions in language through which the phenomena take on meaning, an ontological landscape defined through language.

> As far as we are concerned, ontology recapitulates taxonomy—the way we divide the world in language tells us how we think the world is really put together. (Gregory, 1988, p. 174)

Such an ontological position leads to a situation in which the abstract phenomenon (waves), derived from the concrete entity (water), takes on *meaning* (through the language used to describe it) to become an entity as real as the water itself.

This view of language shifts emphasis in science learning and teaching so that we are less concerned with ontological entities (atoms, electrons) than the metaphors, analogies and stories that surround them. Two important principles derive from this. First, meaning in science is, quite literally, generated in discourse and does not reside independent of it. Second, because hermeneutics allows for multiple interpretations *absolute* meaning is necessarily deferred. This undecidability principle arises because there is always the possibility of 'reading' a text differently. In the following discussion I explore these implications for the development of teacher subject and pedagogical knowledge. In an attempt to illustrate these principles I shall draw on the use of analogy in teaching.

ABSTRACTION AND ANALOGICAL REASONING

The approach to teaching about electricity through analogy is an attempt to make more accessible what is essentially abstract and intangible because it cannot itself be experienced. Only manifestations of it are evident (e.g. a bulb lighting). The teacher, in explaining electricity through analogy, has made a certain decision as to the most effective way to proceed based on pedagogical experience in which analogical reasoning supports learners in critical engagement with abstract phenomena.

However, in locating the object's meaning outside the subject's interpretation, the deployment of analogies in pedagogy to make bridges progressively from base to target domains assumes that there is complete agreement as to the nature of the target concept. This is a highly contentious notion and, in the subject area of electricity, is problematical. Research papers on the role of analogy in promoting understanding of electricity are conspicuous in their lack of qualitative explanation of what the target domain (electricity) actually is. There is an almost implicit assumption that there is complete agreement by science educators as to the nature of the phenomenon. The *science itself* is considered a problem only in regard to cognitive transfer and science education is therefore conceived in terms of pedagogical structures that facilitate acquisition.

This question of meaning is not adequately addressed in the presentation of an 'authoritative' text [see for example the account by Black & Lucas (1993, p. 222) of a physicist's view of simple electric circuits] because that of itself requires an interpretation for which an assumed consensus is precarious in the extreme. This lack of consensus is revealed with even a cursory conceptual exploration and discussion with fellow colleagues about qualitative explanations of simple electric circuits. Interpretation is not only partial but also transient and subjective. In this sense, analogies are mechanisms through which hypotheses are generated rather than proved (Wilbers & Duit, 2001).

It is useful, however, to consider what the research endeavour has focused on and how the analogies are perceived. There is considerable research evidence into the use of analogy in developing understanding in science across a range of phenomena (see for example Gentner & Gentner, 1983; Tiberghein, 1985; Shipstone, 1984; Clement, 1993; Wong, 1993; Cosgrove, 1995; Heywood & Parker, 1997) in science education, particularly in the concept area of electricity. Analogical reasoning in science learning generally is explored in the work of Clement (1993) on a study with high school students' preconceptions in physics and Wong (1993) on trainee teachers' use of their own analogies in generating explanations of physical phenomena. How effective analogies are in promoting understanding of electricity has been researched with children of varying ages (see for example Gentner & Gentner, 1983; Tiberghein, 1985; Shipstone, 1984; Cosgrove, 1995).

In developing qualitative insight into simple electric circuits there is a need to construct a causal mechanism for the concepts of current conservation, energy transfer and resistance. Such causal explanations are highly valued and contain considerable explanatory power (Gilbert *et al.*, 1998) and are significant not only for the student in making sense of science but also for the teacher in developing a synthesis of subject and pedagogical knowledge. I shall return to this point later. However, first a closer look at some traditional approaches aimed at developing qualitative understanding.

APPROACHES TO THE USE OF ANALOGY

The first idea to contend with is that of current conservation, which is a common conceptual difficulty (Tasker & Osborne, 1985). The reason it is difficult and counter-intuitive is because it is natural to think of something material being used up at the bulb; batteries do not last forever. The idea in *isolation* is relatively easy to address and is commonly explained through a range of analogies that include closed systems in water circuits, bicycle chains, moving crowds and the circulatory system. In engaging with this idea, the question that presents itself is what exactly is happening at the bulb if current is conserved? In addressing this question we meet a generic problem in learning: that of conceptualising an abstract idea in relation to other abstract concepts (i.e. current conservation, energy transfer at the bulb and resistance).

The problem is not insurmountable and there is a wide base of literature available that provides commentary on the pragmatics of how this might be achieved. The conservation of current and energy transfer at the bulb as heat and light in a simple circuit is classically explained in analogical terms through variations on a 'moving crowds' model (Gentner & Gentner, 1983), i.e. people representing electrons moving around a circuit (running track) meeting a resistance at a certain point (a narrow stile through which considerable energy is needed to traverse the obstacle) and energy being transferred at that point. Variations in this idea of energy transfer at the point of resistance include motorcycle couriers depositing 'packets of energy' and lorries in a circular run loading at a depot (battery) and delivering the cargo 'energy' at certain locations (analogous to the resistance) then returning to the depot for re-loading.

The pedagogical implications of these and similar approaches have been the subject of considerable debate, most of which has focused on two aspects: first, those analogies that are most effective (see for example Summers *et al.*, 1998) and, second, the process of how analogies work (Clement, 1998; Wilbers & Duit, 2001). In the former the usefulness of an analogy seems largely dependent on whether the base domain resonates with existing experience. Where it does not, transfer to the target domain is obscured through the conceptual demand of the base domain. In the latter case, whilst there is reasonable agreement that the learning process demands the constant juxtaposition from the *base domain* (the analogy) to the *target domain* (the phenomena under scrutiny), there is less consensus concerning the finer nuances of the cognitive mechanisms involved. In either focus, however, it is cognitive transfer rather than the science knowledge itself that is considered problematic.

PARTITIONING AND SEQUENCING

The dilemma in pedagogy centres on how best to address a set of interrelated concepts such as current conservation, resistance and energy transfer. The challenge in explanation concerns the generation of meaning through making accessible complex ideas and this often involves the strategy of building a holistic conceptualisation from constituent parts. In the teaching of electricity through analogy, these ideas are often dealt with separately, however, this differentiating the 'parts' of the 'whole' is not without problems in understanding the nature of how circuits behave, specifically with respect to the difficulties encountered with the sequential view of a circuit. That this is a conceptual hurdle is supported by the findings of Shipstone (1984) and Driver (1994):

> It is notable that prevalent alternative models are sequential models in which something from the battery travels around the circuit, meeting wires and components in sequence. This deep seated notion ... underlies many of the problems which pupils have in understanding the behaviour of electric circuits. It is the notion that might be considered as the underlying mental model having various expressions. (Driver, 1994, p. 120)

In inadvertently promoting a *sequential* rather than a *holistic* qualitative understanding of the workings of a circuit there is raised the issue of how best to avoid such conceptual confusion in promoting an *acceptable scientific model* of explanation. It has been suggested (Lee & Taw, 2001) that conceptualising the circuit in terms of voltage is more appropriate because this enables students to consider the circuit as a holistic system. This view is supported by Frederiksen *et al.* (1999), who argued persuasively through exemplification of student learning that such an approach is qualitatively coherent in derivation from electrostatic to electrodynamic systems. This introduces the idea of electricity as a flow of charge but does not necessarily attend to how this can be conceptualised in respect of causal mechanisms that explain energy transfer at the bulb.

Whatever the pedagogical merits and limitations of preferred models of explanation, the most critical issue is that all analogies break down under critical scrutiny and therefore the focus in pedagogy should be less concerned with the search for the holy grail of analogies to explain the phenomenon of electricity than it is with the reasoning that such analogies generate when they break down at critical points in explanation. This has been argued in detail previously (Heywood & Parker, 1997) and it is reasonable to question the basis of this contention and examine the implications for the presentation of science knowledge in the curriculum.

THE PRESENTATION OF SCIENCE KNOWLEDGE IN SCIENCE EDUCATION

Certainly, $I = V/R$ is a particular way of representing the relationship between current, potential difference and resistance. However, as a causal explanation of what is happening at a qualitative level to make a bulb light in a simple electric circuit, the mathematical expression is particularly limiting in developing a qualitative interpretation of the phenomena of electricity in simple circuits. In hermeneutics the principles of convergence and decidability are relevant in respect of this. In the former, the successive questioning of analogies and the need to adapt the analogy to fit empirical evidence would suggest that meaning awaits expression as to what it (electricity) really is. In this, however, there is exemplified the constraint and possibility of analogy. For, whilst the principle of convergence acknowledges that there is a 'core text' of electricity in existence there to be interpreted, the issue of decidability which permeates those traditions in science, as represented in textbooks and journals, is denied. There is no one version as to how things are. In privileging the interpreter, hermeneutics denies that interpretation is simply *reconstructive*, challenging the notion that meaning is situated in the 'text of science' independent of the interpretive subject. The *meaning* that $I = \frac{V}{R}$ has for both learner and teacher is therefore uniquely *individual* rather than uniquely *apprehensible*.

This allows for a range of possibilities and has significant implications for the presentation of science knowledge in the curriculum. It challenges perceptions of learning and the epistemology of science and points towards a radical shift in emphasis of the role of analogy in science learning. In hermeneutic theory there is a need to recognise the powerful *constraint* and *possibilities* afforded in analogical reasoning. The former is illustrated in the following statement by a student attempting to reconcile the apparent contradictions of a 'tunnel' analogy for resistance in a circuit when applied to two bulbs in series.

> You can only apply the analogy if you are saying the tunnel sometimes becomes larger—you need to view the circuit as a single entity—and the *analogy doesn't allow you* to do this (my emphasis).

This exemplification is a potent reminder of the constraint of language in analogical reasoning that in hermeneutics is a necessary condition of interpretation, for without such constraint there would be no recognition that there was something there to interpret. This is illustrated when an analogy is 'hoist by its own petard' because it resonates so closely with the learner's existing experience that transfer from the base domain to the target domain is considered intrinsically coherent and engagement with the synthesis of ideas that relate to the phenomenon is closed down. In this condition the ontological landscape is determined within the base domain and meaning resides *within* the interpretation of the analogy itself rather than *through* the transfer from base to target domain. What is most significant in this is not that the learner is comfortable or is able to express a scientifically acceptable viewpoint. The issue concerns the *process* of coming to meaning through interpretations that emerge from the quality and incidence of the self-questioning that is generated. This exemplifies the hermeneutic principle of *possibility* afforded in interpretation through analogy. It is in the process of creating this condition, rather than in its explanatory power, that the *potency* of analogy is realised. This has practical implications for the pedagogy outlined below.

PRACTICAL IMPLICATIONS FOR PEDAGOGY: LEARNING

When analogy proves a satisfactory explanation for a ‘part’ of a ‘whole’ (in, for example, the concept of current conservation which seems to actively support a sequential model), the holistic interpretation of the circuit is obscured. The importance of model-based learning (Clement, 2000) is predicated on the notion that there is a need for science to make sense and for a satisfactory coherent explanation to be underpinned by causal mechanisms. However, there are limitations with respect to importing from base to target domain and there is a need to monitor the learning process such that those mechanisms that are imported are appropriate and useful. The tension in this concerns the consensus as to what is considered acceptable. In some instances this is more clearly defined than in others, as, for example, in the concept of current conservation. It is when the particular nature of such a ‘stand alone’ concept is overlaid not only with other concepts, but in respect of them, that consensus becomes contentious. Science educators are probably in broad agreement that there is a need to consider simple circuits holistically rather than sequentially in this regard, but a qualitative causal mechanism that underpins an explanation is far less likely to achieve consensus. The implication of this is that the standard ‘text of science’, when scrutinised beyond surface understanding, is less autonomous in relation to its creation in discourse than is first realised.

This has had significant impact in focusing research attention on the process of conceptual change, with the search for a theoretical model of learning in an effort to identify the factors that influence this process contributing towards the quest for more effective instructional strategies (see Tao & Gunstone, 2000, for a useful summary). Conceptual change theory is in its relative infancy and the mechanisms that underpin concept change can be considered in terms of both learning and teaching. First, I shall explore some of the issues that have been raised recently in respect of learning.

Whilst learners find it difficult to articulate their ideas in terms of supporting them through substantive argument (Kelly & Chen, 1998), there is potential in this process to explore the transient nature of ideas that are generated through the process of articulation itself, i.e. the *act of explanation* necessarily requires scrutiny of the intrinsic coherence of the individual’s rationale underpinning existing interpretations. The focus on models of learners’ explanations that have been described (see for example Solomon, 1986; Metz, 1991; Woodruff & Meyer, 1997) showing a progressive trend from pre-causal to causal explanations which provide the learner with a convincing rationale for the phenomenon under scrutiny are testament to this. In this respect, the notion of learners’ existing ideas or pre-conceptions is somewhat misleading and this is true for both learner and teacher.

A further consideration is that of thought experiments. Reiner & Gilbert (2000) recount the importance of thought experiment in the evolution of ideas in science and suggest that the process offers potential for conceptual development and are a frequently used strategy for problem solving. In developing a thought experiment from practical exploration we are less concerned with the recapitulation of scientifically acceptable ideas established through empirical evidence than we are with the cognitive engagement generated in which understanding is mediated. The thought experiment is in this sense a means of 'testing' the coherence of our own insight in explanation of events. The mechanisms of such processes are complex but certainly warrant consideration in the development of ideas in learning. They are cognitive rather than empirical verifications of hypotheses that again apply equally to teachers and learners.

PRACTICAL IMPLICATIONS FOR PEDAGOGY: TEACHING

The focus on creating a model of conceptual change (Vosniadou, 2001) that can be used to inform teaching strategy has derived from the recognition that developing qualitative understanding is a core predicate for science making sense to the learner. If the knowledge that pupils encounter in science education is not to remain inert, in the sense of bearing no relation to causal explanation of phenomena experienced outside formal science instruction, then the mechanisms that facilitate such change needs to be addressed. One aspect of this concerns engendering a metacognitive approach that requires the learner to examine the assumptions that underpin the cognitive explanatory frameworks that they use to explain the world. This would support them in considering the rational basis of other explanatory models and consider the empirical evidence and intrinsic coherence on which these models are based.

For teaching, this raises the issue of sequence in the order of acquisition of ideas that the student encounters during instruction. This is considered critical across several domains [e.g. particle theory (Johnson, 1999) and astronomy (Vosniadou, 2001)]. There are implications in this regard for both teacher subject and pedagogical knowledge and the nature in which research informs practice. The attendant problems concern a fostering of the delicate symbiotic relation between research and practice in which it is recognised that there are alternative conceptualisations as to what would constitute effective pedagogy in particular domains. For example, the prerequisite for understanding the day/night cycle and the seasons outlined by Vosnaidou (2001) make no reference to the importance of understanding the nature of light and shadow formation. This has been illustrated as particularly significant in supporting learners in developing a coherent, causal mechanism for explaining seasonal change in daylight length (Parker & Heywood, 1998). It does of course raise another issue in respect of conceptual hierarchy concerning whether learners require instruction in the basics of light and shadow prior to undertaking this area of study. A critical point here is the explicit recognition that the sequence of acquisition needs to be informed through research that attends to the learning process itself. The 'science text' subsequently created would therefore necessarily be a consequence of discourse in science learning and teaching. It raises important questions that need to be addressed concerning teacher subject and pedagogical-knowledge.

TEACHER SUBJECT AND PEDAGOGICAL KNOWLEDGE

The remit of teacher education transcends the technological enterprise concerning the practical issues of circuit building or quantitative proficiency in the manipulation of algebraic equations to solve circuit problems. Important though this is, of itself, it does not address how best to support teachers in developing the confidence to engage effectively with children's ideas on simple circuits. Teachers, in supporting learning in which children will have ideas and raise questions about how electric circuits function (e.g. such as what makes a bulb light, why are two bulbs less bright, what causes the battery to go flat?), need to address their own interpretations and qualitative understanding. The development of meaning is integral to and derives from such experience.

A central concern in pedagogy is the need to address the issue of how best to support teachers in developing their own understanding such that the science has meaning for them. Their concerns are often focused on the adequacy of their own explanations in responding to questions raised by pupils. Numerous studies in this area (Osborne & Freyberg, 1985; Osborne *et al.*, 1991) include accounts of pupils' own explanations and reasoning in making sense of what is happening in simple circuits. Easley (1990) reported that children's questions often focus on the mechanisms of how things work and that standard textbook explanations provided little in the way of supporting qualitative understanding in teaching and learning.

There are problems in specifying 'pedagogical knowledge' independent of subject domains. The Initial Teacher Training Curriculum for England and Wales (ITTC) (DfEE, 1998) states that in order to secure pupils' knowledge and understanding of key scientific ideas and the relationships between them, trainees must be taught about the nature of learners' ideas and the relative merits of models, analogies, illustrations, practical work and other methods in securing progress. There is, however, no attempt to relate this to the subject domains. This issue is not necessarily resolved with a shift in emphasis from the focus on teachers' misconceptions towards identifying the knowledge base required for the successful teaching of simple electric circuits to primary children. For example, Summers *et al.* (1998) explicitly identify the subject knowledge base required as the foundation for the teaching of electricity with exemplification from a particular case study based on a particulate approach. They argue that the success of the particular analogy in question (the bicycle chain analogy) is dependent on the pupils' experience and the effectiveness also supports a holistic (systemic) rather than sequential interpretation of circuits. There is a degree of tension in this regarding the acknowledgement within the study as to the inherent problems that arise in supporting the idea of current conservation without consideration of a causal mechanism for energy transfer at the bulb. It is difficult to support their argument for subject-specific teaching knowledge without consideration of what could constitute a *synthesis* of subject and pedagogical knowledge in which the teacher recognises the critical learning elements within particular conceptual frameworks. The explicit identification of what may constitute such a synthesis in specific conceptual domains has been reported in some detail (Parker & Heywood, 2000). An important pragmatic challenge within the remit of evidence-based practice concerns how to achieve this synthesis across the range of phenomena stipulated in the statutory curriculum for science. In addressing the problem, the research emphasis needs to shift focus from determining teachers' misconceptions towards teacher interpretation during the learning process itself. This explicitly acknowledges the teacher as principal interpreter and broadens the scope from concerns with misconceptions, predicated on the notion of recapitulation, towards a focus that attends to the issue of how meaning is generated in science learning and teaching discourse.

Generating qualitative understanding is a task that often remains elusive and there is evidence (Dart *et al.*, 1998) that many university students emerge from degree courses with little but surface declarative knowledge of their discipline. There are significant implications for teacher education in this regard since beliefs about knowledge and learning influence decisions about teaching (Biggs, 1989). An important element of developing pedagogical knowledge is concerned with teachers explicating what they consider to be effective in their learning. In recognising those factors that influence their own learning, that process that has given rise to the metacognition research movement, teachers have been found to question the basis of their own assumptions about what constitutes effective practice. This has been seen to promote conceptual change in the teachers themselves (van Driel *et al.*, 1998) and has implications for what is considered appropriate 'craft knowledge', the most important of which concerns the transitory nature of teacher subject and pedagogical understanding.

CONCLUSION

The emphasis of science knowledge in science education and the recapitulation of that knowledge in which learning is perceived as a *journey towards* meaning that awaits linguistic expression focuses the pedagogical task on a search for the holy grail of analogies. In this model successive analogies would be compared as to their effectiveness in explanation. This detracts from the generative power that intellectual engagement with analogy fosters, situating interpretation and meaning within the context of a *journey towards* rather than a *state of being* in the world. In the former the 'parts' to 'whole' is problematical when an analogy breaks down; in the latter this limitation would be perceived as integral to what meaning is. In this resides the unique contribution of hermeneutics theory to the evolution of the text that is science as presented in science education discourse. It is worth considering here the relation between cognitive resonance and dissonance in the generation of meaning through analogy. Whilst cognitive resonance is seductive, it needs to be considered with caution since the notion that concepts in electricity are uniquely apprehensible is untenable, as the preceding discussion illustrates.

The challenge that confronts both researcher and teacher concerns how teacher subject and pedagogical knowledge can be combined (Fensham, 2001) for effective practice. This synthesis, derived from reflection on the learning process itself (metacognition), requires the interpretation of subject knowledge for appropriate pedagogy and, as such, is the very exemplification of the hermeneutics task. This critical element of science learning is currently being addressed (see for example Parker & Heywood, 2000; Heywood & Parker, 2001) and offers considerable potential to inform the current research paradigm focused on evidence-based practice.

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REFERENCES

BIGGS, J. (1989) Approaches to the enhancement of tertiary teaching, *Higher Education Research and Development*, 8, pp. 7–25.

BLACK, P.J. & LUCAS, A.M. (Eds) (1993) *Children's Informal Ideas in Science* (London, Routledge).

BROWN, T. (1997) *Mathematics Education and Language. Interpreting hermeneutics and post structuralism* (Dordrecht, Kluwer Academic).

CLEMENT, J. (1993) Using bridging analogies and anchoring intuitions to deal with students preconceptions in physics, *Journal of Research in Science Teaching*, 30(10), pp. 1241–1257.

CLEMENT, J. (1998) Expert novice similarities and instruction using analogies, *International Journal of Science Education*, 20(10), pp. 1271–1286.

CLEMENT, J. (2000) Model based learning as a key research area for science education, *International Journal of Science Education*, 22(9), pp. 1041–1053.

COSGROVE, M. (1995) A study in science-in-the-making as students generate an analogy for electricity, *International Journal of Science Education*, 17(3), pp. 295–310.

DART, B.C., BOULTON LEWIS, G.M., BROWNLEE, J.M. & MCCRINDLE, A.R. (1998) Changes in knowledge of learning and teaching through journal writing, *Research Papers in Education*, 13, pp. 291–318.

DFEE (1998) *Initial Teacher Training National Curriculum for primary Science*, annex E of DfEE circular 4/98 (London, Department for Education and Employment).

DREISTADT, R. (1968) An analysis of the use of analogies and metaphors in science, *Journal of Psychology*, 68, pp. 97–116.

DRIVER, R. (1994) Children's ideas about physical processes: electricity, in: R. DRIVER, A. SQUIRES, P. RUSHWORTH & V. WOOD-ROBINSON (Eds) *Making Sense of Secondary Science* (London, Routledge).

EASLEY, J. (1990) Stressing dialogical skill, in: E. DUCKWORTH, J. EASLEY & D. HAWKINS (Eds) *Science Education: a minds-on-approach for the elementary years*, pp. 61–93 (Englewood Cliffs, NJ, Erlbaum).

EGER, M. (1992) Hermeneutics and science education: an introduction, *Science and Education*, 1, pp. 337–348.

EGER, M. (1993a) Hermeneutics as an approach to science: Part 1, *Science and Education*, 2, pp. 1–29.

EGER, M. (1993b) Hermeneutics as an approach to science: Part 2, *Science and Education*, 2, pp. 303–328.

FENSHAM, P.J. (2001) Science content as problematic—issues for research, in: H. BEHRENDT, H. DAHNCKE, R. DUIT, W. GRABER, M. KOMOREK, A. KROSS & P. REISKE (Eds) *Research in Science Education—past, present, and future* (Dordrecht, Kluwer Academic).

FEYNMAN, R.P. (1965) *The Character of Physical Law* (London, Penguin).

FREDERIKSEN, J.R., WHITE, B.Y. & GUTTWILL, J. (1999) Dynamic mental models in learning science: the importance of constructing the derivational linkages among models, *Journal of Research in Science Teaching*, 36(7), pp. 806–836.

GALLAGHER, S. (1992) *Hermeneutics and Education* (Albany, State University of New York Press).

GENTNER, D. & GENTNER, D.R. (1983) Flowing waters or teeming crowds: mental models of electricity, in: D. GENTNER & A. STEVENS (Eds) *Mental Models*, pp. 61–93 (Erlbaum, Englewood Cliffs).

GILBERT, J.K., BOULTER, C. & RUTHERFORD, M. (1998) Models in explanations, Part 1: horses for courses?, *International Journal of Science Education*, 20(1), pp. 83–97.

GOODING, D. (1989) Magnetic curves and the magnetic field, in: D. GOODING, T. PINCH & S. SCHAFFER (Eds) *The Uses of Experiment. Studies in the natural sciences* (Cambridge, Cambridge University Press).

GREGORY, B. (1988) *Inventing Reality. Physics as language* (New York, NY, Wiley).

HEYWOOD, D.S. (2000) Interpretation and meaning in science education: hermeneutic perspectives on language in learning and teaching science, unpublished PhD thesis, Manchester Metropolitan University.

HEYWOOD, D. & PARKER, J. (1997) Confronting the analogy: primary teachers exploring the usefulness of analogies in the teaching and learning of electricity, *International Journal of Science Education*, 19(8), pp. 869–885.

HEYWOOD, D. & PARKER, J. (2001) Describing the cognitive landscape in learning and teaching about forces, *International Journal of Science Education*, in press.

JOHNSON, P. (1999) Children's understanding of substances, Part 1: Recognising chemical change, draft paper delivered at ESRA Conference, University of Kiel, Germany.

KELLY, G.J. and CHEN, C. (1998) Students' reasoning about electricity: combining performance assessments with argumentation analysis, *International Journal of Science Education*, 20(7), pp. 849–871.

KUHN, T.S. (1970) *The Structure of Scientific Revolutions* (Chicago, IL, University of Chicago Press).

LEE, Y. & TAW, N. (2001) Explorations in promoting conceptual change in electrical concepts via ontological category shift, *International Journal of Science Education*, 23(2), pp. 111–149.

METZ, K. (1991) Development of explanation: incremental and fundamental changes in children's physics knowledge, *Journal of Research in Science Teaching*, 28, pp. 785–798.

OSBORNE, J., BLACK, P., SMITH, M. & MEADOWS, J. (1991) *Science Processes and Concept Exploration Project: research report: electricity* (Liverpool, Liverpool University Press).

OSBORNE, R. & FREYBERG, P. (1985) *Learning in Science. The implications of children's science* (Auckland, Heinemann).

PARKER, J. & HEYWOOD, D. (1998) The earth and beyond: developing primary teachers' understanding of basic astronomical events, *International Journal of Science Education*, 20(5), pp. 503–520.

PARKER, J. & HEYWOOD, D. (2000) Exploring the relationship between subject knowledge and pedagogic content knowledge in primary teachers' learning about forces, *International Journal of Science Education*, 22(1), pp. 89–111.

PFUNDT, H. & DUIT, R. (1984) *Bibliography: Students' Alternative Frameworks and Science Education*, 4th edn (Kiel, Germany, IPN).

POPPER, K.R. (1963) *Conjectures and Refutations* (London, Routledge).

REINER, M. & GILBERT, J. (2000) Epistemological resources for thought experimentation in science learning, *International Journal of Science Education*, 22(5), pp. 489–506.

SHIPSTONE, M. (1984) A study of children's understanding of electricity in simple D.C. circuits. *European Journal of Science Education*, 6, pp. 185–195.

SOLOMON, J. (1986) Children's explanations, *Oxford Review of Education*, 12, pp. 41–51.

SUMMERS, M., KRUGER, C. & MANT, J. (1998) Teaching electricity effectively in the primary school: a case study, *International Journal of Science Education*, 20(2), pp. 153–172.

TASKER, R. & OSBORNE, R. (1985) Science teaching and science learning, in: R. OSBORNE & P. FREYBERG (Eds) *Learning in Science* (Auckland, New Zealand, Heinemann).

TAO, P. & GUNSTONE, R.F. (2000) The process of conceptual change in forces and motion during computer supported physics instruction, *Journal of Research in Science and Technology*, 36(7), pp. 859–882.

TIBERGHIEN, A. (1985) Some features of children's ideas and their implications for teaching, in: R. DRIVER, E. GUESNE & A. TIBERGHIEN (Eds) *Children's Ideas in Science*, pp. 1–9 and 193–201 (Buckingham, Open University Press).

VAN DRIEL, J.H., VERLOOP, N. & DE VOS, W. (1998) Developing science teachers' pedagogical content knowledge, *Journal of Research in Science Teaching*, 35(6), pp. 673–695.

VOSNIADOU, S. (2001) Conceptual change research and the teaching of science, in: H. BEHRENDT, H. DAHNCKE, R. DUIT, W. GRABER, M. KOMOREK, A. KROSS & P. REISKE (Eds) *Research in Science Education—past, present, and future* (Dordrecht, Kluwer Academic).

WILBERS, J. & DUIT, R. (2001) On the micro-structure of analogical reasoning: the case of understanding chaotic systems, in: H. BEHRENDT, H. DAHNCKE, R. DUIT, W. GRABER, M. KOMOREK, A. KROSS & P. REISKE (Eds) *Research in Science Education—past, present, and future* (Dordrecht, Kluwer Academic).

WOLPERT, L. (1992) *The Unnatural Nature of Science* (London, Faber & Faber).

WONG, D.E. (1993) Understanding the generative capacity as analogies as a tool for explanation, *Journal of Research in Science Teaching*, 30(10), pp. 1259–1272.

WOODRUFF, E. & MEYER, K. (1997) Explanation from intra- and inter-group discourse: students building knowledge in the science classroom, *Research in Science Education*, 27, pp. 25–39.