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ABSTRACT

This paper aims to clarify and describe the process of change in learners' conceptual understanding of natural phenomena. It begins by reviewing the existing literature on models of conceptual change and on children's conceptions in a number of selected topic areas. Strategies for exploring and developing children's ideas in these areas have also been clarified and developed, and computer software that could be useful in exploring children's reasoning and promoting conceptual change is identified. A range of intervention strategies has been devised to promote conceptual change, focusing on the use of computer-based methods. The document's section headings are: (1) "The Overview of the Research"; (2) "The Research Collaboration"; (3) "Background to the Field of Study"; (4) "Topic Domains Selected for Study"; (5) "The Role of Computer Based Activities in Promoting Conceptual Change"; (6) "Software Tools"; and (7) "Phasing of the Work." Appended is a list of Centre for Information Technology in Education (CITE) reports. (Author/KR)

Centre for Information Technology in Education

Information Technology in Education: Conceptual change in Science

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Information Technology in Education:
Conceptual change in Science

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PROJECT TITLE: CONCEPTUAL CHANGE IN SCIENCE

1. OVERVIEW OF THE RESEARCH

The research aims to clarify and describe the process of change in learners' conceptual understandings of natural phenomena. It will begin by reviewing the existing literature on models of conceptual change and on children's conceptions in a number of selected topic areas. Strategies for exploring and developing children's ideas in these areas will also be clarified and developed, and computer software which could be useful in exploring children's reasoning and promoting conceptual change will be identified.

From this review, two or possibly three topic areas will be selected, where progress in understanding involves different types of conceptual change. For each area, the prior conceptions of a number of children will be explored in some details with a range of phenomena and will be documented using talk-aloud protocols.

A range of intervention strategies will be devised to promote conceptual change, focusing on the use of computer-based methods and approaches based on ARK-like and STELLA-like software. [An outline of the properties of these tools is provided later.] Detailed protocols of the outcomes of these interventions will be produced from a video and audio tape record. The extent of conceptual change will be assessed by readministration of the original tasks; and the protocols of the intervention strategies will be analysed also, to develop a theoretical description of the change process.

The analyses from all the selected topic domains will be used to develop a more general description of the processes involved in conceptual change, and hypotheses arising from this work will be tested with other groups of children through experimental studies.

2. THE RESEARCH COLLABORATION

The research will involve collaboration between groups at the Universities of Leeds and Glasgow and the Open University. Each of these groups will make distinct contributions to the programme.

Glasgow University will concentrate on producing ARK-like software for use by the other members of the consortium. It will carry out studies of the user interface from both the teacher's and the pupil's viewpoint, studying and extending the theory of Direct Manipulation. Hence, it will address the theoretical issue of the psychological relationship between factors promoting conceptual change on the one hand, and ease of use of the software on the other.

Leeds University will focus on the studies of childrens' conceptualisations in the topic areas, on the interventions for conceptual change, on the design/development of software tools (primarily STELLA-based) and will participate in the evaluation studies.

Primarily, the Open University will carry out classroom experiments using simulations constructed with ARK-like software and will extend that software to make it usable by different communities, including pupils, teachers and educational researchers.

3. BACKGROUND TO THE FIELD OF STUDY

3.1 Children's Informal Theories

Research studies undertaken over the last twenty years have indicated that children develop informal theories about natural phenomena prior to being taught science in school (Driver, Guesne and Tiberghien, 1985). These informal theories appear to derive from children's direct experiences with phenomena and are supported by everyday discourse and the media.

The nature of these informal theories has now been documented for a wide range of domains in science including physical, biological and earth sciences, and certain common features have been identified. For example:

(i) children's informal theories may differ significantly from accepted scientific theories yet they may be consistent within the limited range of experiences of the child (eg. the informal theory that motion requires a force is consistent with much experience in a world with friction)

(ii) informal theories tend to be used in ad hoc and context dependent ways (Engel-Clough and Driver 1986)

(iii) they tend to be implicit rather than explicit in the way children interact with and describe phenomena.

Research on children's informal theories can be interpreted within a cognitive science perspective (Carey, 1986). A central feature of this interpretation is that human beings construct 'mental representations' of objects and events in their environment and these are used to make sense of new situations. Developmental studies of children's informal theories document the change that takes place as children progressively reconstruct their 'mental representations' of natural phenomena (Carey, 1985). Domains where this progressive reconstruction of 'mental representations' has been documented include: light and sight (Guesne, 1985); matter (Holding, 1987); heat and temperature (Strauss and Stavy, 1982); the characteristics of living things (Carey, 1985). Some initiatives are being taken to put forward coherent accounts of the development of these 'mental representations' (for example see diSessa, 1987).

From an educational perspective, knowledge and understanding of children's prior theories is seen as important because of the influence these have on subsequent learning. There is evidence for example that in certain domains such as mechanics, informal theories can persist among University physics students (Viennot, 1979) despite instruction. This research field has led science educators to reconceptualize science learning as involving a process of conceptual change (Hewson and Hewson, 1983).

3.2 Informal Theories and Classroom Learning

A number of studies has been undertaken to promote the process of conceptual change in science in classroom settings in various topic areas including mechanics (Champagne, Gunstone and Klopfer, 1985), electrical circuits (Shipstone, 1985; Arnold and Millar, 1987) and particle theory of matter (Nussbaum and Novick, 1982). The Children's Learning in Science Project has devised and evaluated conceptual change approaches to teaching topics of plant nutrition, energy and particle theory of matter (CLIS, 1987). In all these studies, children's prior conceptions have been acknowledged as starting points in the schemes of work. Children have been given opportunities to make their ideas explicit and to clarify them. They have then undertaken a range of activities designed to promote a restructuring of their ideas and finally have been given opportunities to consolidate and review their models. Although some successes have been reported in these studies, the pedagogical strategies which have been adopted have tended to be eclectic and have not necessarily led to a greater understanding of the dynamics of the processes of change.

3.3 Models of Conceptual Change

A number of models is currently being put forward to describe and account for the conceptual change process. In some cases the models are based on an individualistic perspective on learning, in other cases the model of change sets the learner within the context of a social group. Within the individualistic perspective, the Piagetian model of equilibration has received considerable attention by science educators. This model proposes that learners, when confronted with discrepant information, will attempt to adjust their conception in order to resolve the conflict. The limitation of this model is that it does not address the issue of the origin of any revised conception.

Some theorists (eg. Claxton, 1982) suggest that, rather than change their conceptions from one form to another, learners have a range of available conceptions which are selected as they are seen to apply to specific situations. This places an emphasis, in learning, on developing an awareness of the context in which certain conceptions are appropriate. Karmiloff-Smith (1984) proposes a model for change which does not involve conflict. In outline she suggests that after learners achieve successful, if ad hoc, solutions to separate tasks within a class of problem, they will then reflect on these and 'try to understand why certain procedures are successful, unpacking what is implicit in them, and unifying separate instances of success into a single framework' (p.40). It is thus the combination of successful experiences and the opportunity to reflect on these which enables change to take place. Again, however, the focus of enquiry is not on the process of construction of the new conception.

In a careful study of conceptual change in the context of solving statics problems in physics, Brown and Clement (1987) investigate the place of analogies in promoting conceptual change and in particular investigate which analogies are useful to students in acting as bridges to new conceptions. Other models of change place emphasis on the explicit role of instruction. Based on Vygotsky's notion of scaffolding, Heller and Hungate (1984) report how University students are enabled to analyse mechanics problems from a Newtonian perspective through coaching. Other studies identify the social processes which need to be taken into account in the learning process. Edwards and Mercer (1987) argue this point:

> "However active a part pupils are allowed to play in their learning, we cannot assume that they can simply re-invent that culture through their own activity and experience. It is necessarily a social and communicative process and one which has as an inherent part of it an asymmetry of roles between teacher and learner."

4. TOPIC DOMAINS SELECTED FOR STUDY

The study will focus on domains with different characteristics concerning the nature of the conceptual change involved. For example, in some topic areas, change may involve the learner in moving from an alternative conception towards the more general accepted scientific view; in others, it may involve changes in the learner's ability to use a complex analogic model to explain observed phenomena; in some, it may involve change in the ability to relate a quantitative (probably algebraic) mathematical model of a system to a more qualitative verbal description.

Domains which would be appropriate are the following:

(i) Force, motion and energy transfer.
The idea that a force is needed to maintain steady motion persists in many learners' understanding of motion. Conceptual change involves the identification of friction as a force, and a move towards associating force with change of motion rather than with motion per se. Language use and everyday experience contribute to the widely shared view that energy is used up in many processes. Conceptual change would involve the discrimination of the ideas of conservation and

dissipation of energy, and a greater ability to interpret common phenomena in terms of these two ideas, rather than that of energy consumption.

(ii) Particulate theory of matter and conservation of matter. Children often adopt the terminology of 'particles' but meet severe conceptual hurdles concerning the properties and behaviour of these particles. This is reflected in uncertainties about how and why the particles move, what is between them, how they are held together in solids, how their movement gives rise to the pressure exerted by gases. As a result children often have difficulty in providing explanations for macroscopic phenomena in terms of the behaviour and properties of invisible particles. Conceptual change would involve the development of greater facility in using accepted particle ideas to account for a range of common phenomena involving gases. Many children hold the alternative conception that matter/mass/weight is lost when substances dissolve, and that the total matter/mass/weight of the products of a chemical reaction may differ from that of the reagents. Conceptual change would involve movement towards the accepted view that matter is conserved in situations of this sort.

Related to this is the topic of:
Air and air pressure. Common alternative conceptions include the idea of vacuum as an active agent and that air has no weight or has negative weight. Phenomena are explained in terms of 'suction' in preference to the scientific account in terms of atmospheric pressure and pressure differentials; balloons are predicted to float or move upwards because the air they contain is not seen as having weight. Conceptual change would involve movement towards the accepted scientific conceptions.

5. THE ROLE OF COMPUTER BASED ACTIVITIES IN PROMOTING CONCEPTUAL CHANGE

Computer models should have a contribution to make both to the study of children's scientific thinking and in promoting conceptual change for the following reasons:

(i) they require children to make their implicit reasoning explicit (through, for example, simulations of object motion or collisions).

(ii) they enable children to visualise the consequences of their reasoning and provide an object for reflection and communication with others.

(iii) they provide pictorial representations and dynamic displays of models of phenomena which could form useful bridging analogies.

(iv) data logging and display facilities can provide rapid numerical or graphic representations of how variables are inter-related in on-going situations.

A key feature for investigation would be the relation perceived by children between computer simulations and the physical phenomena they represent. Studies using computer simulations which specifically address children's misconceptions have been reported in the literature in the areas of motion (diSessa, 1982; White 1983); electrical conductivity (White and Frederiksen, 1985); heat and temperature (Wiser 1988).

Also of interest would be the ways students use qualitative reasoning and how they develop more formal and quantitative statements in refining their models (Forbes and Stevens, 1981; Rivers and Vockell, 1987). Within qualitative reasoning, we expect to distinguish functional statements (concerned with goals, and how the model tries to achieve them) and causal statements on state-changes. We shall further examine whether students are able to operate at different levels of generality, taking a holistic view of the model's functioning and a particularist view of its component processes. Students often get confused about scope (wondering if changes to one component will affect another) [de Kleer 1987]. Other features of students' working, which have been apparent in our preliminary studies, are default-reasoning, (i.e. how students maintain their ideas and arguments by using suppositions which do not follow strictly from previous knowledge) and abduction (eg. when the gas was hydrogen it bubbled off: this gas is bubbling off so it will be hydrogen.) Though not logical and though they may become possible sources of misconceptions, abduction and default reasoning can prove to be useful growth-points for ideas and hypothesis testing (Forbes and Stevens, 1981). We aim to study the prevalence and consequences of these reasoning techniques.

For software tools interface design is of crucial importance, but has been a sorely neglected issue in educational (software) research. As Frye and Soloway (1987) note, the interface of a piece of educational software must provide an entry to the content domain rather than vice versa. 'Interface' in this respect refers to the way in which those characteristics that make up the 'system image' (Norman, 1986) induce the development of the appropriate mental model of the (micro)world it is intended to represent. The term 'system image' covers what the user does with the system (i.e. the physical actions of manipulating the mouse, etc) as well as what it looks like.

The interface is the only way in which the user can operate in the represented world. If it is designed appropriately, the interface becomes transparent and no longer exists for the user. The (represented) world becomes, cognitively, directly present to the user. This is the notion of 'direct manipulation' (DM) which has recently enjoyed some attention in human-computer interaction (HCI). The theory is still in an early stage of development - so far it has been worked out only from the viewpoint of users familiar with the represented domain. A crucial educational issue, therefore, is how to design DM interfaces for exploratory learning that are effective in teaching unfamiliar concepts/domains, and in dealing with misconceptions.

The term 'direct manipulation' was first used by Shneiderman (1983) to refer to interfaces with the following properties: continuous representation of items of interest; physical actions instead of complex syntax; reversible operations; immediate feedback. Hutchins et al (1985) distinguish between two aspects of 'directness' in DM interfaces: distance and direct engagement. Distance refers to the gap between the user's goals or intentions and system task - the actions the user has to perform in order to use the system. This gap is two-fold: the 'gulf of execution' between intentions and actions, and the 'gulf of evaluation' between outcomes and intentions. The better the interface to the system bridges these gulfs, the less cognitive effort is required and the more direct the interaction feels. Direct engagement refers to the more qualitative aspects of DM: the feeling that one is operating directly in the world of interest (i.e. the model world).

The theory distinguishes further between two forms of directness. Semantic directness is the relationship between the user's intentions and the meaning of an expression in the interface language (i.e. the operations required.) Two aspects of this are: whether the language (either via commands, menus or mouse cliks) supports to user's conception (model) of the task domain, and whether the user can specify intentions in a straightforward way (i.e. without complex constructions.) Articulatory directness refers to the relationship between the meanings of expressions and their physical form (this is more than just syntax, but includes the sensorimotor aspects of processing - hence the term articulatory).

In the language of Hutchins et al, semantic directness facilitates the externalisation and subsequent manipulation (and re-interiorisation) of concepts; articulatory directness allows for the development of cognitive structures or representations through the sensorimotor processes of joint perception and action. Acting directly in the (micro)world allows users to appropriate and internalise the concepts represented in that world.

According to the theory of Hutchins et al, successful direct manipulation depends on achieving articulatory and semantic directness. The latter means mapping from object. and operations of the system (of the simulated world) to concepts already known to the user. However, in educational contexts, the concepts modelled by the system are not yet known to the user. The issue is then, that the system should be easy to use for some other reason, so that the user can learn the concepts needed to operate the system and thereby appropriate the concepts modelled by it (since these are semantically mapped to concepts 'in the world').

If the system is to be easy to use without the user understanding in advance the concepts represented by it, we need to pay attention to other kinds of directness - i.e. articulatory directness. Relatively little attention has been paid to this until recently (eg. Buxton, 1986; Scaife, 1987). This aspect of DM concerns the natural divisions of sensorimotor tasks (i.e. 'low level' actions and the feedback that controls them), how these map into existing skills on the one hand, and the tasks set by the system on the other.

However, this is probably not enough in itself. In considering how direct manipulation systems might be effective for exploratory learning, we may need to develop a distinction between deep and shallow semantic directness. Deep semantic directness means accurate and unobscured mapping of concepts; shallow semantic directness means a recognisable mapping of the learner's existing concepts to the system. A learner might, for instance, not yet understand a physical law properly, but will have an idea about what an object is, and of some of its familiar qualitative behaviour. Presumably, successful learning depends upon attaching to and building on this. It is necessary to think carefully about how and when to introduce simulations depending on their agreement with intuition. Counter-intuitive behaviour may simply rupture the user's belief in the simulated world. On the other hand, introducing such conflicts may be important in convincing the learner to abandon naive and incorrect models.

6. SOFTWARE TOOLS

Are direct manipulation devices more useful to school students in the learning of physics than experience of the real world? This may indeed be the case, as some observations from real experience lead to the induction of incorrect laws. Real world experience is highly complex - involving the interaction of multiple forces (friction, gravity, etc) acting simultaneously. One suggestion is to present students with simpler microworlds (cf. diSessa, 1982; White, 1984), but even idealised environments may be too complicated. Overcoming this may require allowing the student to manipulate each of the constraints and variables individually, altering them and experimenting to see how they interact.

The idea of direct manipulation environments for exploring concepts in the physical sciences was first conceived nearly 400 years ago by Francis Bacon, in the form of a science centre described in his unfinished work The New Atlantis (Bacon, 1624.) Eighteen years ago Oppenheimer established the 'exploratorium' in San Francisco, and more recently Richard Gregory founded the exploratory in Bristol - a centre where people can explore ideas about the natural sciences. A computer based environment for exploring physics now exists in the form of the 'Alternate Reality Kit' (ARK). However whereas the San Francisco and Bristol exploratoria are stuck with the laws of nature, ARK allows users to vary physical laws, such as Newton's laws of gravity, Hooke's Law, etc.

ARK (Smith, 1986) is a system implemented in Smalltalk-80 for creating interactive animated simulations. It is built on a metaphor from the physical world in which all objects have a visual image, a position, a velocity and are operated on by physical forces. Everything in ARK can be manipulated according to the constraints of physical laws, in faithful simulation of the real world. It differs from the real world in that the physical laws can be changed. Thus, users can create artificial microworlds within the ARK environment with which to compare the physical laws governing the real world, and explore how they interact with one another.

ARK microworlds are distinguished from existing instructional programming languages and educational microworlds (such as Logo, Prolog and the various extensions to them) in two ways. First, ARK is uniformly concrete - all objects in ARK appear as entities with position, velocity and the ability to respond to forces. The physical representation of objects extends through the whole system. Second, ARK is naturally extensible. The routine way of extending ARK microworlds is to directly manipulate the objects in them. This contrasts with conventional instructional programming environments which demand additional sophistication of the user who wishes to generate new procedures or data structures from within the microworld.

Scanlon and Smith (in press) used ARK to introduce users who had little or no physics training to the behaviour of particles in a bubble chamber. Students were able to make deductions about elementary particles using information about charge conservation, particle tracks and the behaviour of charged particles in magnetic fields. ARK has also been used in a series of experiments (O'Shea and Smith, 1987) on student misconceptions of conservation of momentum. Pairs of students working with an ARK simulation were able to improve their understanding of conservation laws.

For aiding the development and testing of cognitive models, a useful and powerful modelling package - STELLA - is available on the Apple Macintosh, and makes full use of its interfacing capabilities. (Previous work at the Open University shows that schoolchildren in the age-range of the proposed research learn to operate the interface after only a short training time.) STELLA, which has been used with schoolchildren in acid rain and pollution projects, allows students to draw and specify data-store/data-flow models with connecting arcs controlled by functions. Arrows are used to indicate direction of flow, and the functions can be expressed directly, or by curve drawing on the screen. (STELLA outputs can be stored in forms compatible with other Macintosh wordprocessing and document production packages.)

Although STELLA is a powerful tool which gives good dynamic displays and has wide applications across the curriculum, it operates with quantitative functions and the development of the model has to be planned and discussed off-line. We propose to support these stages of thinking by using, where appropriate, ARK-like materials to experiment with the processes In addition, we aim to build a small software 'knowledge-bench' where students can set up a state-change model with procedures expressed as (qualitative) rules governing these state changes. This bench model, when initiated, will attempt to run (and provide feedback) qualitatively, thus giving an analogue demonstration of the working model proposed by the students. The purpose of the 'knowledge-bench' is to encourage and support qualitative reasoning; this understanding can then be extended and refined quantitatively through STELLA.

7. PHASING OF THE WORK

Initial phase (Autumn 1988 - Spring 1989)
This will include reviewing the literature on models of conceptual change and children's conceptions in the selected domains. An analysis of the curriculum context in which concepts in the selected domains are used in secondary school science courses will also be undertaken. The features of the ARK and STELLA software tools will be appraised with this framework in mind, using small experimental studies. Hence a rationale for the development of the design characteristics of the software tools will be outlined.

Development phase (Spring 1989 - Summer 1990)
The development of the software tools will be undertaken in this phase informed by small scale explorations with children. These will simulate the features of the interface and of qualitative reasoning which are of particular interest. Parallel with this, classroom based studies of conceptual change in the selected domains with secondary school children will be undertaken to gain insight into these cognitive processes. These data will inform the ways software tools and associated materials can bring about such conceptual changes in children's understanding.

Evaluation Phase (Spring 1989 - Autumn 1991)
As the software tools and their methodologies are developed, evaluation studies will be undertaken in schools examining both the processes of conceptual change and evaluating the effectiveness of the intervention in promoting learning. In this respect we anticipate that working will take place in groups and the ways the interventions influence group interactions will also be examined.
Other aspects to be investigated at this stage would include evaluation of the interface characteristics and usability with teachers, and the broader curriculum contexts in which the tools and methodologies might be applied. Evaluation work will also be carried out with Shopping-On-Mars a direc manipulation system for arithmetic to determine the age range that such interfaces are suitable for, and to explore the way small groups of pupils work with direct manipulation systems.

For dissemination the group will contribute to seminars, and also produce research papers and reports for teachers. Additionally we envisage the materials and research findings contributing to in-service training provision.

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