

Critiquing a framework in principled software design

PhD Examination 2012

Angela Hall

ABSTRACT

This study uses educational design principles to interrogate an electronic tutorial from the Salters-Nuffield Advanced Biology resources. The tutorial is based on Hammerling's historic experiment on the single-celled alga, *Acetabularia*. This leads to a critique of design principles, some outline revisions to these principles, and to a reconstruction of the tutorial.

Data from students using the tutorial was recorded and transcribed, and pre- and post-tutorial test data and written tasks were also used. Cognitive barriers and opportunities were identified through repeated inductive analyses to produce and refine a task model for the tutorial. The initial analysis highlighted multiple phenomena of interest, so the scope of the study was narrowed to focus on how students use background science ideas to develop scientific explanations. The next stage of analysis involved a comparison of the data with an existing set of scaffolding design principles. These principles provided a framework for analysis of the scaffolding present in the tutorial, and suggested where the generic principles needed more detail or exemplification.

The outcomes of the study include a methodology which uses design guidelines to analyse and refine the electronic tutorial. Where gaps in the guidelines were revealed in this process, revisions to the framework for analysis are suggested. The final chapters suggest a way of defining and exemplifying the content knowledge of educational design and making this knowledge explicit during the process of design.

The study raised broader issues relating to the vocabulary used by science educators to discuss science inquiry and content. It is also suggested that the guidelines in the framework exemplify a flawed model of 'the scientific method' that has commonly been accepted for use in curriculum design for science inquiry learning.

CONTENTS

CHAPTER 1 AN INTRODUCTION TO THE STUDY	9
1.1 The context of the study.....	9
1.2 Comparing educational research and educational design research	10
1.2.1 The role of design principles	11
1.2.2 The knowledge base of educational design	11
1.2.3 Educational design research	13
1.2.4 Synthesising knowledge from educational design research	14
1.3 Design guidelines for scaffolding learning	15
1.3.1 A description of the framework.....	16
1.3.2 Scaffolding sense making.....	17
1.3.3 Scaffolding process management.....	17
1.3.4 Scaffolding articulation and reflection.....	19
1.3.5 The scope and utility of the framework.....	19
1.4 Salters-Nuffield Advanced Biology (SNAB)	20
1.4.1 Context-led courses	20
1.4.2 The context of the software development	21
1.5 Evaluation report on the SNAB pilot.....	23
1.6 Description of the <i>Acetabularia</i> tutorial.....	25
1.6.1 Presenting the experiments.....	25
1.6.2 Formative assessment in the tutorial	27
1.7 Setting the research questions for study	29
CHAPTER 2 THEORIES UNDERPINNING THE STUDY	32
2.1 Introduction	32
2.2 Applying knowledge about how students learn in educational design	33
2.3 Scaffolding learning	36
2.3.1 Scaffolding as an educational metaphor	36
2.3.2 Apprenticeship as a model of scaffolded learning.....	38
2.4 Learning through science inquiry.....	41
2.4.1 Developing scientific knowledge and skills	41
2.4.2 The educational purpose of science inquiry	42
2.4.3 The content to be learnt through science inquiry	44
2.5 Developing scientific ideas	48
2.5.1 Developing explanations.....	48
2.5.2 The big stories in science	50
2.5.3 Construction of mental models	54
2.6 Supporting students as they resituate prior learning.....	61
2.6.1 Situated cognition	61
2.6.2 Scaffolding to support resituating of learning	62

2.7 Cognitive load	65
2.7.1 Cognitive load imposed by complex learning	65
2.7.2 Conceptual problems with cognitive load theories	66
2.8 Conclusions from the review of the literature	68
CHAPTER 3 DEVELOPING A METHODOLOGY FOR PRINCIPLED SOFTWARE DESIGN	70
3.1 Introduction to the methodology	70
3.1.1 My position as researcher	70
3.1.2 Learning from the pilot studies	71
3.1.3 A summary of the methodology and methods	76
3.2 Stage 1: Developing the task model for the tutorial	77
3.2.1 The task decomposition	79
3.2.2 Using the task decomposition to analyse individual screens	81
3.3 Stage 2: Collecting the empirical data	83
3.3.1 Screen capture software as a tool for research	83
3.3.2 Data from Centre A	87
3.3.3 Transcribing the recordings	89
3.4 Stage 3: Analysis of the data	90
3.4.1 The strategies available for analysis	90
3.4.2 Strategies used for analysis in this study	91
3.4.3 Categorising the themes	92
3.4.4 Producing generalisations from the data	95
3.4.5 Finding a focus for the study	96
3.5 Stage 4: Testing the framework using the data	97
3.6 Stages 5 and 6: Recommendations and evaluation	98
3.7 Ethical considerations	99
3.8 Conclusions from this chapter	100
CHAPTER 4 ANALYSING THE DATA USING THE TUTORIAL'S TASK MODEL	102
4.1 Evidence for prior learning	102
4.2 Evidence of learning from the tutorial	106
4.2.1 Background science	107
4.2.2 Context-specific learning	112
4.2.3 Skills used in scientific inquiry processes	119
4.3 Summary of students' learning	128
CHAPTER 5 THE UTILITY OF THE SCAFFOLDING DESIGN FRAMEWORK.....	131
5.1 A summary of the study so far	131

5.1.1 Findings from the data	131
5.1.2 The focus of this study	132
5.2 Revisions to the task model for the next stage	132
5.3 Establishing the entities involved in a specific inquiry	137
5.3.1 Establishing <i>Acetabularia</i> as an ontological entity	138
5.3.2 Testing Quintana <i>et al.</i> 's Guideline 1 to support the establishing of entities	142
5.3.3 Testing Quintana <i>et al.</i> 's Guideline 5 to support the establishing of entities	151
5.4 Using the methods of scientific inquiry and reasoning to manipulate the entities, to collect data and to make inferences from the data	152
5.4.1 Testing Quintana <i>et al.</i> 's Guideline 3 to support an understanding of the inquiry question ..	153
5.4.2 Testing Quintana <i>et al.</i> 's Guideline 4 to support scaffolding of complex inquiry tasks	157
5.5 Supporting science explanations	167
5.5.1 Testing Quintana <i>et al.</i> 's Guideline 7	167
5.6 Conclusions from the study	175
CHAPTER 6 INFERENCES FROM THE STUDY	179
6.1 The knowledge of designers	179
6.1.1 Inferences suggesting revisions to the framework	179
6.1.2 The pedagogic underpinning of design	179
6.2 Expert procedural knowledge of the discipline	181
6.2.1 The uncertainty around a task model for explanations	181
6.3 The need for expert knowledge of science content	183
6.4 Professional pedagogical knowledge	184
6.5 Professional design knowledge	185
6.5.1 Craft knowledge of the discipline	185
6.5.2 PCDK of explanations	186
6.6 Didaktik as a model for PCK.....	187
6.6.1 A Didaktik analysis of the Quintana <i>et al.</i> framework	189
6.7 Revising the framework for design	192
6.7.1 A summary of the revisions to the tutorial and framework	192
6.7.2 A holistic didactical framework for design	193
6.8 Didactical designs for the revisions	196
6.8.1 Applying the didactical framework to revisions of the tutorial	196
6.8.2 Establishing the protagonists	201
6.8.3 A model-based inquiry version of the experiments	201
6.9 Presenting the PCDK.....	210
6.9.1 Displaying complex information and relationships	213
6.10 Summary of inferences from this study	216
CHAPTER 7 REFLECTIONS AND IDEAS FOR FURTHER WORK.....	219

7.1 Contributions of the thesis	219
7.2 Evaluating a methodology for principled educational design	219
7.2.1 The review of the literature	220
7.3 Testing the scope of the framework	221
7.4 The utility of the framework	223
7.5 Limitations of the research	224
7.6 Ideas for further work	226
7.6.1 The role of teachers	226
7.6.2 Scaffolding articulation and reflection	231
7.6.3 Exemplifying barriers and lack of scaffolding	233
7.6.4 Articulating tasks and subtasks at a sufficient level of detail	234
7.6.5 Scaffolding background science ideas	234
7.6.6 PCDK.....	235
7.6.7 Establishing and maintaining a community for educational design	235
Bibliography	237
Appendix 1	251
Appendix 2	252
Appendix 3	253
Appendix 4	254
Appendix 5	255
Appendix 6	257
Appendix 7	265
Appendix 8	272
Appendix 9	280
Appendix 10	281

TABLE OF FIGURES

Figure 1.1 Guideline 1 from the Quintana <i>et al.</i> framework	18
Figure 1.2 Screen 1 of the <i>Acetabularia</i> tutorial	26
Figure 1.3 Three screens showing the manipulables and animation of the first experiment	26
Figure 1.4 Animation after Experiment 4 in the tutorial	28
Figure 1.5 Question following Experiment 2 in the tutorial	28
Figure 1.6 Final question after Experiment 4 in the tutorial	29
Figure 2.1 Gestalt figure	57
Figure 2.2 Visual of Acetabularia used in the tutorial	58
Figure 2.3 Atkinson and Shiffrin's multi-store model of memory	65
Figure 3.1 A <i>ScreenFlash</i> screen showing a recording of students carrying out the tutorial	86
Figure 3.2 Initial analysis of transcripts using sticky notes	93
Figure 3.3 Screen 1 of the <i>Acetabularia</i> tutorial	96
Figure 4.1 Screen 30: Question after Experiment 4	109
Figure 4.2 A multiple choice question after Experiment 2 (screen 12)	122
Figure 4.3 Multiple choice question after Experiment 2 (screen 14)	123
Figure 5.1 Screen 1 introduces <i>Acetabularia</i>	148
Figure 5.2 Multiple choice question after Experiment 2	160
Figure 6.1 Pedagogic content design knowledge	186

Figure 6.2 Hudson's (2008) didactical model for technology supported learning.....	188
Figure 6.3 An adaptation of the Hudson (2008) didactical model showing the elements of PCDK ..	195
Figure 6.4 Summary of Hammerling's Experiment 1.....	202
Figure 6.5 Summary of Hammerling's Experiment 2.....	203
Figure 6.6 Hint button summarising experiment 1	204
Figure 6.7 Hint box to support students' interpretation of Experiment 1	205
Figure 6.8 Summary of Hammerling's Experiment 3.....	205
Figure 6.9 Workbench for Experiment 3 showing roll-over guidance on the pipette tool.....	206
Figure 6.10 Summary of Hammerling's Experiment 4.....	207
Figure 6.11 Workbench for Experiment 4 with two species of <i>Acetabularia</i>	208
Figure 6.12 RSC's Compass tool in 'Discover Maths'	214
Figure 6.13 Spicynodes screens which show drilling into a topic (design of software).....	215

LIST OF TABLES

Table 3.1 Decomposition of Question 3 in the <i>Acetabularia</i> tutorial	82
Table 3.2 Summary of data collected	89
Table 3.3 An example of transcripts cut from screens 11 and 12	94
Table 4.1 Data showing references to cell parts and to <i>Acetabularia</i> as a plant	116
Table 5.1 The narrative of an inquiry leading to an explanation for development in <i>Acetabularia</i> ..	135
Table 5.2 Task model elements involved in establishing the entities	137
Table 5.3 Task model elements involved in scientific inquiry	153
Table 5.4 Task model elements for developing broad schemas for science topics	167
Table 6.1 Summary activity for revised tutorial	209
Table 6.2 A model for presenting the PCDK exemplified by revised Experiment 3	210

Declaration: I hereby declare that, except where explicit attribution is made, the work presented in this thesis is entirely my own.



Word count (exclusive of appendices and bibliography) = 76,532

Acknowledgements

I would like to acknowledge the role of Professor Michael Reiss in persuading me that I should and could start a research degree in the first place. On discussion of this plan with Dr. Ralph Levinson, Ralph encouraged the idea by immediately offering to supervise my thesis. I am indebted to both Ralph and Professor Diana Laurillard for their stimulating and critical supervision of my work, and to Michael for carrying out an independent reading of my thesis prior to submission.

I am very grateful to the institutions which allowed me to collect data, and to the individual students who were so willing to take part in this study. I would also like to acknowledge the support I have had from my places of work, firstly the Institute of Education, where I was working at Science Learning Centre, London as I started my thesis, then more recently at the Nuffield Foundation.

Last but not least I would like to thank my husband, Martin, and my children, Simon, Tom and Rose for putting up with me burying myself in my study, and for their unfailing love, understanding and support during this venture.

Chapter 1 An introduction to the study

1.1 The context of the study

This thesis represents my contribution to a shared aim of the educational design community concerning the development of generalisable design principles. After more than 10 years involvement in educational design, and in my current role apprenticing new designers into the craft, I suggest that it is only through the distillation of these principles that new work will consistently and effectively build on previous designs.

The focus of this study is an electronic tutorial which was designed as part of the Salters-Nuffield Advanced Biology (SNAB) course resources. I was involved in the development of this course and its resources after leaving teaching to join the (then) Nuffield Curriculum Projects Centre as an inexperienced designer. My particular responsibility was for the development of the electronic resources for the SNAB course website.

Although I was able to base ideas for designs on existing work, I was not necessarily able to identify the key features and principles which underpin good design. Without a concerted effort on the behalf of designers to identify and share this expert knowledge, the induction and apprenticeship of new designers is not as efficient as it could be. Even for expert designers, articulation of the design process is a valuable activity, as it allows them and others to learn from their experience.

The methodology used in this study tests a set of existing generalised principles which aim to guide the design of software tools for scaffolding learning through science inquiry. This study demonstrates how, during design and refinement of a learning resource, the effectiveness of individual tools can only be judged in relation to specific intended learning outcomes. The challenge being addressed is how to develop design principles from this type of study of learning within a specific context.

The electronic SNAB tutorial analysed in this study involves students in Hammerling's classic inquiry using the single-celled alga *Acetabularia*. It exemplifies complex learning through scientific inquiry, utilising a range of software tools. The study of the tutorial raises questions which are pertinent to software developers and to science education more generally. In particular, the nature of learning through science inquiry is explored.

highlighting the difficulties in discussing this domain due to lack of agreed definitions of the learning tasks involved.

The question of whether an electronic tutorial can involve learners in aspects of science inquiry is discussed. For example, the outcomes of the study suggest that authentic inquiry tasks can be isolated, taught and practised independently from a whole inquiry. How students' learning through software can be studied is also at the heart of this thesis. This question is crucial if educators are to become better informed about the role of electronic tutorials and the as yet ill-defined role of teachers as they seek to complement the role of computers within the wider learning environment.

The first stages of the study describe the cognitive tasks associated with the SNAB *Acetabularia* tutorial. Learning and barriers to learning are identified from empirical data with reference to this task model. Data from students carrying out the tutorial is¹ then analysed with reference to an existing scaffolding design framework, testing the framework's affordance for guiding revisions of a specific software tutorial. The framework is described later in this chapter (Section 1.3.1) and the methodology for collecting the data is described in Chapter 3.

This chapter sets the context for the study by describing the need to accumulate a knowledge base about educational design, and to develop, test and refine design principles. It goes on to describe the development of electronic materials as part of the SNAB course. Finally, the tutorial being studied is described, to provide sufficient detail for readers to appreciate the descriptions of the tasks and students' interactions with the tutorial in later chapters.

1.2 Comparing educational research and educational design research

When I came to educational design, I had some intuitive ideas based on experience of classroom practice. However, good quality educational design draws on pedagogic knowledge to produce resources which make the connection between educational theory and practice (Davis and Krajcik, 2005). My knowledge base of underpinning theories and experience of good practice in design was certainly not developed.

¹ In this thesis, 'data' is treated as a singular mass noun, to reflect modern English usage, for example in The New Oxford English Dictionary (2001).

I found little explicit guidance for the processes of design and development. Discussion of what makes good design frequently focuses on subsystems of the product, such as assessment for learning, and on general principles such as 'scaffolding' and 'encouraging active learning'. Designers have rarely succeeded in articulating sub-components in a way that makes meaningful steps in the design process explicit for the benefit of other designers. There is a need for more rigorous reflections on design (Schunn, 2008), and this thesis aims to contribute to this process.

1.2.1 The role of design principles

When I first started to read the literature on educational design, I found no shortage of generic design principles in the literature. Wiggins (1999) sets out guidelines for design of curriculum, assessment and instruction based on 'backwards design' leading from learning goals. Black and Wiliam focus on building on what students already know through assessment for learning (Black and Wiliam, 1998). Others have developed guidelines in, for example, design using multiple representations and multi-media (Askew *et al.*, 1997; Plowman *et al.*, 1999; Mayer and Moreno, 2003) and good practice for designing feedback (Nicol and MacFarlane-Dick, 2006). Bransford *et al.* draw on theories of educational psychology to inform design of learning environments (Bransford *et al.*, 2006).

Design principles are intended to orientate rather than dictate detail of a design. The final product relies on the designer interpreting the principles, in addition to creative input based on prior experience and imaginative extensions from it. Systematic development through feedback from trials is a crucial element of good design and this process is much more difficult to describe generically (Swan, 2008).

As I found when first seeking guidance, design principles are often overly generic, making them hard to interpret in practice, or overly specific, tied to the contexts of the development. This makes it hard to reinterpret them for evaluation and reuse (Laurillard and Ljubojevic, 2009). To put design principles into practice, a designer needs a solid theoretical perspective and specific knowledge of the issue to hand, along with design skills: two talents rarely found in one individual (Schoenfeld, 2009).

1.2.2 The knowledge base of educational design

Educational design is a profession with a knowledge base but also includes craft knowledge. Educational design principles are underpinned by theory, which in turn is grounded in educational research. Without this scholarship associated with design, it would remain a

craft², which relies on each generation learning through apprenticeship from the previous experts, much as I learnt my craft through the curriculum development work I was engaged in from 2001.

Eraut (2007) argues that professions are more easily described as applied fields than as disciplines. He contrasts the knowledge base of an applied field with that of a discipline: an applied field draws on a knowledge base across many disciplines, where the knowledge base of a discipline consists largely of codified knowledge in books and journals. Science education, for example, draws on disciplines which include psychology, linguistics, sociology and science. A profession such as educational design does, though, generate its own knowledge base through empirical research, practical principles and articulation of the ideology of the profession.

I am now in the position of Director of curriculum development at the Nuffield Foundation, with a remit to pass on ideas about educational design to new designers. This experience has demonstrated how there is tacit knowledge in addition to formal knowledge involved in any craft or profession, and that this knowledge is frequently difficult to pin down (Frayling, 2006). It is also clear that learning an applied discipline such as educational design through apprenticeship can be very successful for some individuals, but it is not necessarily an efficient method of training. Although this rarely happens in educational design in the UK, explicit instruction can be a more efficient way of sharing expertise, within and between organisations (Ericsson and Charness, 1994). This sharing relies on experts articulating the knowledge to be transferred.

Schunn (2008) compares educational design with the process of engineering products. He concludes that, while there are clearly differences in the end product, there is considerable scholarship and formal education on engineering design processes. This contrasts with a lack of scholarship and formal training in educational design, presenting a capacity issue for organisations such as the Nuffield Foundation wishing to recruit designers, and to pass on knowledge of educational design to new generations of designers.

If organisations such as the Nuffield Foundation are to succeed in articulating the relevant knowledge base as generalised design principles, we need to articulate these at an appropriate level of subsystems. There are many ways of breaking down an overall system

2 The English word 'craft' is defined as something between an art which relies on talent, and a 'science' which relies on 'knowledge'.

into subsystems, depending on the theoretical models of teaching and learning underpinning the design. Schunn (2008), for example, sees good subsystem decomposition as where each subsystem can be defined in terms of a clear functional goal. Each subsystem also needs its own metrics and potential for separate testing against these metrics.

The Wright brothers, in designing their first aeroplane, followed a design heuristic which was decomposed to a level which was useful for design. They designed and tested separate subsystems of aircraft, such as wing shapes, control mechanisms and propulsion mechanisms. By contrast, their less successful competitors always tested whole airplanes (Weber, 2006).

As we engineer educational resources, this should involve a similar consideration of how the subsystems contribute to the whole, and should consider heuristics based on the experience of successful designers. At the core of educational design is working out we can implement ideas from educational research in the classroom. This involves an approach to design which interfaces with educational research in both its focus and its methodologies.

This thesis contributes to the field of educational design by testing an existing design framework against empirical data, in a process which aims to exemplify how such a framework can provide guidance for principled design.

1.2.3 Educational design research

Educational design research goes beyond the remit of educational design, which is interested in whether an intervention works, and how to improve it. Educational design research methods focus on the contextualised interactions between an intervention and learner which inform educational design. The aim is to synthesise the knowledge base by establishing principles for design, generalising from specific studies. Design experiments, which support the development and exploration of interventions, are a context for contributions from both the educational research community and the educational design community (Schoenfeld, 2009).

Design experiments using educational interventions seek to explain differences in outcomes in terms of differences between individual design features. They also attempt to explain why a particular feature contributes to a specific outcome, while acknowledging that learning is too complex to identify the precise contribution of a particular learning experience (Reeves, 2011). This does not remove the need for educational designers to actively develop methodologies which illuminate common features of effective learning tools,

leading to generalised design principles. Reeves' point can be addressed by providing multiple exemplars illustrating how generalised principles are enacted in different contexts. This helps to define the scope and utility of particular tools and principles. Designers' expert practise then involves translating the information from these principles and exemplars into the context in which they are working.

Quintana *et al.* (2004) developed a framework to provide principles for scaffolding design across the whole range of software for learning through science inquiry. Scaffolding is discussed further in Chapter 2 (see Section 2.3) where it is defined as support which allows learners to go beyond what they could achieve alone. The framework is an example of where design and research collaborate to produce principles for design, based on understanding of learning and barriers to learning from educational research. The guidelines synthesise approaches to supporting inquiry learning to produce generalised strategies for design.

The overlap in educational design research and educational research lies in the shared techniques used to find out what students make of learning experiences. In design experiments this is with the aim of improving a particular product. The design of the intervention which led to any observed effects is of interest to educational designers in addition to the underpinning theory which explains its effect (Schoenfeld, 2009). In educational research, the educational resource is usually a tool for theorising about how students learn through a particular approach rather than the end product of the research. The pragmatic aim of educational design research, leading to a product, acknowledges the importance of principled and theory based processes. Developing principled guidelines for design involves synthesising and applying educational research.

1.2.4 Synthesising knowledge from educational design research

Any attempt to synthesise heuristics or guidelines for design must be content-free to be useful to designers. Cases which exemplify the general principles in specific contexts are, however, useful as a guide to applying the heuristics. The guidelines in the Quintana *et al.* (2004) framework generalise approaches to supporting particular aspects of learning through inquiry. These approaches are exemplified through a variety of software, showing how the guidelines apply in a range of contexts. One way of testing the scope of generalised guidelines is to compare their fit with further specific software examples. This is one aspect of this study, where the methodology involves testing the framework using empirical data from students using the *Acetabularia* tutorial. The methodological approaches used in this

study are typical of those suggested by the purposes of educational design research. These favour more qualitative methods, which allow researchers to explore the effects of interventions and the processes that result in their affordances (Schoenfeld, 2009).

The approaches suitable for educational design research contrast with the traditional emphasis in educational research on randomised controlled trials. In the past, these studies aimed to make 'steady, irreversible progress' in aspects of educational practice (Slavin, 2002 p. 19). Examples of large scale studies which have influenced educational policy in England include the recent policy tie between a definition of effective education and performance in Standardised Assessment Tasks (SATs) (Radford, 2006). Radford concludes that, contrary to the assumed promise of reductionist analytical methods, these studies based on narrow tests of achievement can't provide the type of specific information needed to inform policy and practice. It should not be assumed that, in educational situations, elements work together in a linear and causal relationship. Instead, rich descriptions and explanations that provide a broader perspective on development are needed.

To elicit findings which are useful to educational designers, small scale studies providing rich descriptions of learning in specific situations are needed, rather than large scale studies which may offer 'rigour' at the expense of 'relevance' (Russell, 2001). At least these two types of study need to work in a complementary way to provide inferences about educational practice that are both rigorous and relevant.

Through a small-scale and detailed exploration of the scaffolding within a particular electronic tutorial from the SNAB resources, this study aims to throw light on how generic guidelines can be of use to designers.

1.3 Design guidelines for scaffolding learning

The Quintana *et al.* (2004) framework provides guidelines to support design of software scaffolding. Other frameworks exist for software design, design of scaffolding and for inquiry learning. These combine models of learning with design principles, with reference to relevant studies (Honebein, Duffy and Fishman, 1993; Bransford, Brown and Cocking, 2000; Herrington and Oliver, 2000; Linn and Hsi, 2000; Edelson, 2002; Linn, Davis and Bell, 2004; Azevedo *et al.*, 2005; Puntambekar and Hübscher, 2005).

The relevance and utility of the Quintana *et al.* (2004) framework for the purpose of this study is in its meta-analysis of ideas from previous frameworks and studies of learning. It

provides a synthesis of theoretical and empirical investigations of scaffolding approaches in the specific context of learning through science inquiry.

The framework directly reflects this study's context: design of support for learning through science inquiry. The argument for selecting a previously constructed framework implies acceptance of the theoretical underpinning of its construction. Quintana *et al.* (*ibid*) defend their design framework in terms of a theoretical analysis of the literature on learning and instruction, obstacles learners face in inquiry learning and the nature of pedagogical support.

In particular, they draw on the instructional approach of cognitive apprenticeship (Collins, Brown and Newman, 1989; Bruner, 1996) where students are coached alongside expert guidance and cognitive perspectives of learning (Anderson, 1983). Social constructivism (Vygotsky, 1978) and situated learning theories (Lave and Wenger, 1991) are drawn upon, with their view of learning as involving socially situated tasks and dialogue. Scaffolding is viewed in the Vygotskian sense of enabling learners to achieve more complex tasks than they could achieve unsupported (Vygotsky, 1978).

The methodology of this study is informed by the process Quintana *et al.* (2004) followed in developing their guidelines. For example, both the framework and this study produced task models for science inquiry learning which provide a reference for identifying evidence of learning and barriers to learning.

1.3.1 A description of the framework

The Quintana *et al.* (2004) framework is organised around three main constituent processes of science inquiry identified from the literature: sense making, process management, and articulation and reflection. Within these categorisations, the cognitive tasks of inquiry are characterised. Scaffolding approaches are suggested as strategies to support these cognitive tasks, and software tools which exemplify the approaches are described. In this way, seven scaffolding design guidelines and twenty scaffolding strategies are provided.

An inductive analysis of a range of scaffolding tools from software supporting science inquiry learning led to the synthesis of the scaffolding approaches suggested in the framework. The task model for learning through science inquiry and the aspects of the tasks where learners encounter obstacles were characterised from the literature on

reasoning and inquiry learning. The task model provided the three organising processes for the framework described above.

The guidance in the framework describes approaches to scaffolding barriers to learning. As the categorisation is according to pedagogic approaches rather than software features, a particular tool may appear in more than one category, and each category exemplifies a range of different types of software tool. Figure 1.1 shows how the guidelines, strategies and software examples are presented in the framework for Guideline 1.

1.3.2 Scaffolding sense making

Sense making refers to the tasks of science inquiry leading to inferences and explanations of the data. The tasks identified from the literature for this category in the framework include generating hypotheses, designing comparisons, reasoning, making observations, and analysing and interpreting data. The emphasis of Guidelines 1-3 in this section of the framework is on the processes involved in making sense of data. This reflects the generic nature of a framework which applies across inquiry in a wide range of science topics:

Guideline 1: Use representations and language that bridges learners' understanding.

Guideline 2: Organise tools and artefacts around the semantics of the discipline.

Guideline 3: Use representations that learners can inspect in different ways to reveal important properties of underlying data.

(Quintana et al., 2004, p. 345)

The next category in the framework provides guidelines which address the management of science inquiry.

1.3.3 Scaffolding process management

Quintana et al. (*ibid*) point out that scientific inquiry is not a neatly structured pursuit. The nature of scientific inquiry and learning through scientific inquiry is discussed in detail in Section 2.4. Inquiry is often ill-defined as a process, often complex, and usually requires iterative development of explanations over a long period of time. It requires a large number of separate operations, and needs to constantly refer back to previous work and accepted theories which help to make sense of the data. Managing this process is more critical as a result of the complex nature of the work.

Figure 1.1 Guideline 1 from the Quintana *et al.* framework (Quintana *et al.*, 2004, p. 348)

Software Examples of Guideline 1: Use Representations and Language That Bridge Learners' Understanding

Software	Description
Scaffolding Strategy 1a: Provide visual conceptual organizers to give access to functionality WorldWatcher	WorldWatcher (Edelson, Gordin, & Pea, 1999) uses an energy balance diagram to help students understand what factors are relevant to investigate and reason about what data to consider next
Astronomy Village	Astronomy Village, a software environment for space science, uses visual scenes from laboratories to organize access to data from satellites and solar system probes (Dimitrov, McGee, & Howard, 2002)
Scaffolding Strategy 1b: Use descriptions of complex concepts that build on learners' intuitive ideas Model-It™	Model-It™ (Metcalf, Krajcik, & Soloway, 2000; Stratford, Krajcik, & Soloway, 1998) replaces quantitative expressions with qualitative language when students are building relations between variables in a model
ThinkerTools	ThinkerTools conveys the notion of acceleration to students by having moving objects in a simulation leave a visual trace of equally timed marks (White, 1984)
BioKIDS CyberTracker	The CyberTracker software uses "taxonomic common sense" to allow students to categorize animals with accurate, but understandable, intuitive classification schemes and language rather than traditional biological classification schemes (Parr, Jones, & Songer, 2002)
Scaffolding Strategy 1c: Embed expert guidance to help learners use and apply science content KIE and WISE	The "Mildred" guide in KIE gives students content hints in the form of questions to think about or thought experiments to do; the WISE learning environment (Linn & Slotta, 2000) provides similar hints
Knowledge Mediator Framework	The Knowledge Mediator Framework (Jacobson, Sugimoto, & Archodidou, 1996) presents annotated examples that include "expert commentaries" explaining how a scientific construct is applied in the example
Why2-Atlas	The Why2-Atlas system for teaching qualitative physics features a coach that tries to identify and address different student misconceptions about physics by engaging in a dialog with the student, essentially modeling to the student how an expert might reason about different physics concepts (VanLehn <i>et al.</i> , 2002)

Note. KIE = Knowledge Integration Environment; WISE = Web-Based Inquiry Science Environment

Quintana *et al.* (*ibid*) identify a series of barriers to process management from the literature. These include lack of domain-specific knowledge of the activities involved, and lack of strategic skills to make the necessary decisions on how to proceed. Students can find the complexity of inquiry overwhelming, so identifying and prioritising significant tasks over distracting managerial 'chores' is an area of need in learners.

Guidelines 4-6 provide strategies for limiting the tasks by structuring and restricting the activities which students need to engage in, by providing expert guidance and by minimising distractions, to allow deep engagement with the process:

Guideline 4: Provide structure for complex tasks and functionality.

Guideline 5: Embed expert guidance about scientific practices.

Guideline 6: Automatically handle non-salient, routine tasks.

(Quintana *et al.*, 2004, p. 345)

The third organising category of the framework from the task model includes guidelines for design of scaffolding to encourage articulation and reflection.

1.3.4 Scaffolding articulation and reflection

The single guideline under this area of the framework acknowledges the role of articulating the reasoning which contributes to synthesising explanations in science inquiry:

Guideline 7: Facilitate ongoing articulation and reflection during investigation

(Quintana *et al.*, 2004, p. 345)

The strategies under Guideline 7 encourage use of reminders to articulate and reflect at key points in an inquiry, and guidance to support understanding of the discourse used in science. This discourse involves, for example, explaining, interpreting and describing (Lemke, 1990).

1.3.5 The scope and utility of the framework

The interface between research in the domain of science inquiry learning and research into the tools and approaches which support this learning is critical to establish a theoretical underpinning for educational design research (Edelson, 2002). The Quintana *et al.* (2004) scaffolding design framework, as a meta-analysis of studies in relevant areas, provides a common theoretical framework to guide scaffolding design in software to support inquiry.

Quintana *et al.* (*ibid*) challenge designers to test the framework's utility and comprehensiveness, inviting revisions which broaden its scope.

The next section contributes to the context of this study through a description of the Salters-Nuffield Advanced Biology course, for which the electronic tutorial being studied was designed.

1.4 Salters-Nuffield Advanced Biology (SNAB)

SNAB belongs in the suite of Salters context-led advanced level science courses. It is distinctive among other biology courses at this level in that it uses topical applications and stories to introduce biological content as it becomes relevant to understanding the scenario. The SNAB project also encourages active learning through a comprehensive set of activities designed for the course.

1.4.1 Context-led courses

The storyline approach to teaching science was developed in Salters GCSE and advanced science projects, Salters Advanced Chemistry (SAC) and Salters Horners Advanced Physics (SHAP) which preceded SNAB.

The Salters-Nuffield Advanced Biology (SNAB) project was launched in September 2000 by the University of York and The Nuffield Curriculum Projects Centre. I joined Nuffield in January 2001, as the project officer with particular responsibility for the electronic component of the resources. We piloted the course from September 2002 for three years, and revised the specification and resources in the light of feedback from the pilot schools and colleges. A third development phase for SNAB started in 2007 in response to QCA³'s revision of the advanced science specifications for first teaching in September 2008. This provided an opportunity for me to implement the early findings from this study into the revised SNAB ICT tutorials. Specifically, I revised the *Acetabularia* tutorial to incorporate some richer guidance and feedback, for example.

Nuffield Advanced Biology (Monger, 1986), predecessor of SNAB along with the Salters courses, was developed in the 1970s based on a discovery approach to learning. Elements of the Nuffield approach influenced future specifications, and some original Nuffield

³ The Qualification and Curriculum Authority

activities live on in a revised form in SNAB. The *Acetabularia* tutorial which is central to this study was originally a paper-based activity within the Nuffield A level biology resources.

The *Acetabularia* tutorial uses a classic experiment as a context for introducing ideas about the processes of science and how scientific knowledge is arrived at. The tutorial, based on Hammerling's experiments on *Acetabularia*, is described in Section 1.6.

While Salters context-led science courses have been evaluated as effective (Bennett *et al.*, 2002) there may be a problem with 'relevance' that is discussed later in this study. If biological topics are introduced as a result of their relevance to a storyline, this can present a risk to the epistemological coherence of the science. Science topics are often introduced with some element of context, but the emphasis on real life contexts and applications of science is particularly strong in Salters courses. The risk is, that if learning about DNA and protein synthesis is strongly situated within ideas about inheritance of cystic fibrosis during learning in one topic, resituating it to a different context such as cell development in a later topic may be problematic. The coherence of protein synthesis as a science concept may not be appreciated as fully in a context-led course compared with an approach that starts with the science and illustrates this through multiple contexts. There is a balance to be struck between relevance and coherence.

In addition to developing a particular approach to learning biology, as developers of SNAB we took a position on the role of ICT in an advanced level biology course. The next section describes the electronic resources which were developed for the course.

1.4.2 The context of the software development

Technology is part of the daily lives of most young people. Information and Communications Technology (ICT) is ubiquitous to the extent that we are not always fully aware of its presence or its role in our activities. One estimate suggests that by the age of 21 the average person will have spent 15,000 hours in formal education, 20,000 hours in front of the TV, and 50,000 hours in front of a computer screen (Green *et al.*, 2005). Access to technologies has changed the way young people engage with informal learning and communications, but has not yet been mirrored in the formal education system.

At the start of the SNAB development (year 2000), most school laboratories had at most a single computer for use by the teacher at the front of the class, and class access to computers relied on booking a computer room. Internet access increased rapidly, so by 2008, 16 million (65%) households in Great Britain had internet access, compared with 46%

in 2002 (Directgov, 2008). As virtual learning environments (VLEs) began to appear in schools, the link between school and home began to be bridged by the internet. The potential to provide a comprehensive set of resources online was exciting, as most schools and colleges used a mix and match of resources of varying quality and relevance to the courses being taught. By 2007, virtually all schools had networks and broadband connectivity (BECTA, 2007).

The rapid increase in access to computers and internet in schools was partly due to a greatly increased level of government funding for ICT from 1998. It was obvious to the SNAB team that any major curriculum development should attempt to look ahead by at least 5 years rather than designing for the current landscape. Even so, we were nervous of ICT facilities being a requirement of the course, or of any technical expertise on the part of teachers being necessary.

Science teachers traditionally show a tendency towards didactic, whole class teaching approaches (Donnelly, 1999). The literature is rich in studies of how ICT may or may not support learning in terms of raising achievement, and the affordances of particular applications or hardware. But, there is less research on the role of ICT in changing the overall teaching and learning practices in science education. It could be argued that the full potential of ICT to change these approaches has not yet been fully exploited.

The opportunities for learning in schools and colleges represented by new technologies come with their own benefits and risks. As curriculum developers and commercial publishers focus increasing resources on developing the role of technologies in learning, there is a need for any perceived benefits or affordances⁴ of ICT to be empirically verified.

This thesis is a critical review of the process of curriculum development in the context of software tools and the affordances of design guidelines. The study represents an opportunity for detailed reflection on a specific curriculum development. As a curriculum project funded through a partnership between funding charities, a commercial publisher and an awarding body, the constraints of time and budget in the development of SNAB were

⁴ The term 'affordance' has come to be popular in the field of human-computer interactions, meaning the quality of an artefact which allows it to perform a particular action or function. The term affordance is used here in the discussion of the features of ICT that encourage particular ways of learning, and particular types of interaction or classroom practices.

less than may normally be associated with developments carried out by individual commercial organisations in response to curriculum changes. Even so it represents a fast pace of development compared with educational research studies that focus on individual aspects of interventions over a period of months. This study specifically offers insights into the affordances of ICT tools for scaffolding science inquiry learning by considering a single SNAB tutorial.

1.5 Evaluation report on the SNAB pilot

The electronic component of the SNAB course consists of paper downloads and electronic tutorials within a virtual learning environment (VLE). The VLE provides functionality for communications, and assessment through electronic marking.

During the pilot phase, an external evaluation of the SNAB course was carried out by Jenny Lewis, from the Centre for Studies in Science and Mathematics Education, School of Education, University of Leeds. Evaluation questions were developed after discussion with the SNAB development team. In the area of ICT, the initial questions were:

There is a strong ICT element designed to support both student centred learning and the general management of the course. To what extent, and in what ways, is it actually being used? Is any additional support or training needed? Does the provision of online interactive tutorials change the nature/focus of the teacher-pupil relationship in the classroom?

(Lewis, 2004)

It is clear from the pilot that teachers face a more demanding role as managers of a learning environment that includes ICT. Even with a comprehensive set of resources available, the teacher has to make decisions about when to stand back or intervene, and how much structure and guidance should be given to pupils. Any change in pedagogy is 'expensive' in terms of teacher's time and effort (Collins, Hammond and Wellington, 1997).

The SNAB pilot evaluation drew attention to the need for professional development in the use of ICT tutorials. Producing good quality curriculum resources alone does not necessarily bring about change. With inadequate support, teachers will revert to traditional methods (OECD, 2001).

The evaluation found that the ways in which ICT resources were being used in the pilot schools varied considerably both from teacher to teacher and between students. There was little evidence that they were being used in any systematic way to free up class time for

small group or one to one work which could focus more directly on the needs of individual students (*ibid*).

Recommendations from the pilot suggested that teachers would benefit from guidance on how to use ICT resources to encourage successful independent learning, and discussion of how this might change the focus of teaching in the classroom (*ibid*).

Problems with access to hardware and technical support, confidence in using ICT and management of the necessary changes in pedagogy required to integrate SNAB into biology classes were largely overcome by the majority of teachers over the course of the pilot. Teachers and students fed back their enthusiasm for the software, which is seen as one of the strengths of the SNAB resources. The pilot evaluation report, referring to use of ICT tutorials, reported:

... all teachers managed to use some of the resources, particularly animations and worksheets and all teachers recognised the quality and potential benefits of the IT resources developed by SNAB.

(Lewis, 2004, p. 66)

Students and teachers were very positive about their experiences of using SNAB electronic tutorials. Tutorials were deployed in a variety of different ways, including individual student learning, homework and class use, groups or pairs of students working together and teacher at the front using a data projector (Lewis, 2004).

But, the evaluation provided little reflection from students or teachers on why or how they thought the SNAB tutorials helped learning. The role of this type of evaluation includes accountability to funders and signals a commitment to quality assurance. Evaluation studies also collect and analyse data which could inform areas for future developments broadly. For example, it was possible to conclude from the SNAB evaluation that science teachers were ready for a comprehensive web-based resource to support advanced level teaching.

However, evaluation in this model does not help to establish or utilise educational design principles and processes. The question of what design principles underpin the affordances of the SNAB tutorials was not addressed in the evaluation, so there is little knowledge gained from the evaluation to inform future revisions or new developments.

The SNAB electronic resources represent a wide range of different types of activity. From the point of view of informing future development, it is not useful to make generalisations from a study across the entire SNAB resource about affordances of ICT. There may be

common effects, such as the motivating factors associated with students working on a computer (Becta, 2003), but these may be present in any similar software. There may also be effects to do with classroom organisation when groups are at computers: classroom management alters the role of the teacher and the pedagogy.

There will inevitably be effects particular to the SNAB resource being studied and to its science content. The nature of the cognitive tasks that students are being asked to take part in is likely to be as important as the medium of the resource. A description of the tutorial is provided in the next section, and a detailed decomposition of the cognitive tasks involved is described in the methodology, in Chapter 3.

1.6 Description of the *Acetabularia* tutorial

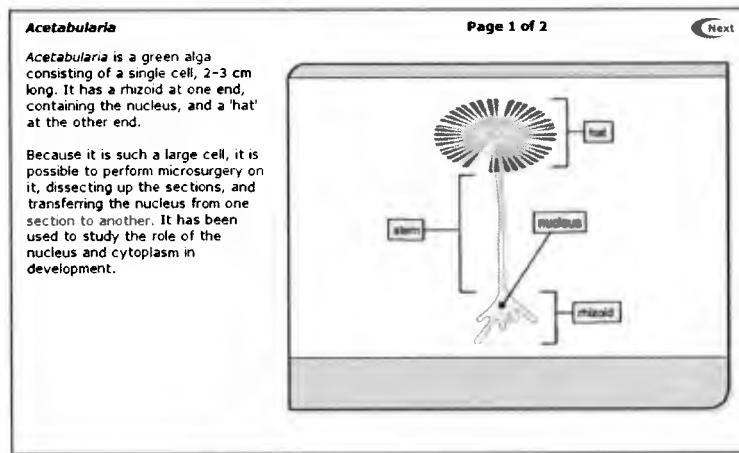
The *Acetabularia* activity occurs in the third of four topics in the first year of the two year SNAB course. Topic 3 (The voice of the genome) covers the story of development from a fertilised egg to human baby. The tutorial is based on Hammerling's four classic experiments that provided evidence for which part of a cell controls development. The experiments introduce the idea that chemicals coded for in the DNA have an effect on a cell's development at a distance.

The experiments are presented in structured steps, through visuals and interactive animations. Multiple choice questions with feedback test students' understanding after each exposition of an experiment.

1.6.1 Presenting the experiments

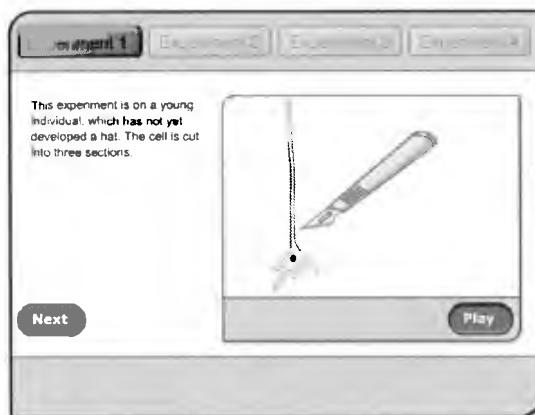
Hammerling worked on the alga *Acetabularia* from the late 1930s. *Acetabularia* is a unicellular organism, chosen by Hammerling because it is large enough to allow manipulation of the nucleus and cell parts. The 2-3 cm cell has three sections; the rhizoid (containing the nucleus), stem and hat. The organism and the aims of the inquiry are introduced on Screen 1 of the tutorial (Figure 1.2).

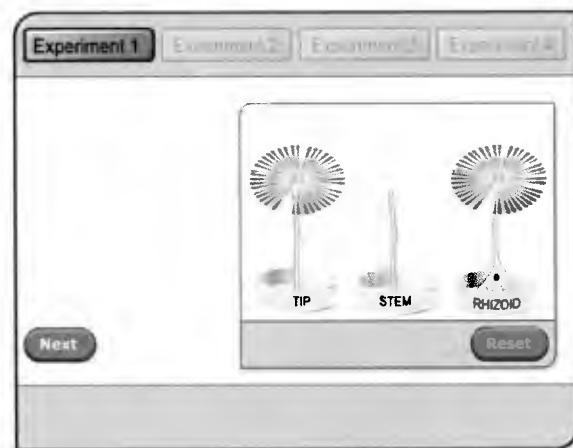
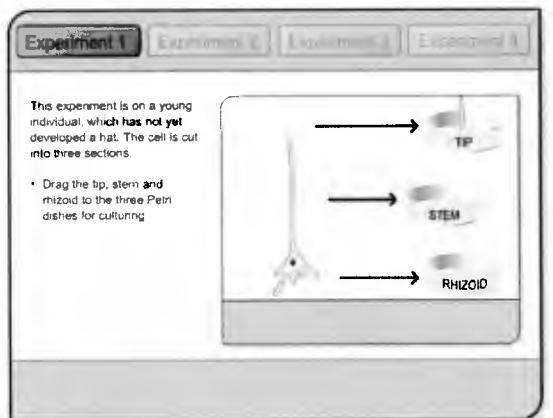
Figure 1.2 Screen 1 of the *Acetabularia* tutorial



The electronic tutorial provides a manipulable representation of Hammerling's experiments. Users can remove the hat and rhizoid of *Acetabularia*, using a virtual scalpel. They can drag the separate cell parts to a Petri dish where an animation runs, showing them how each part developed (Figure 1.3).

Figure 1.3 Three screens showing the manipulables and animation of the first experiment





1.6.2 Formative assessment in the tutorial

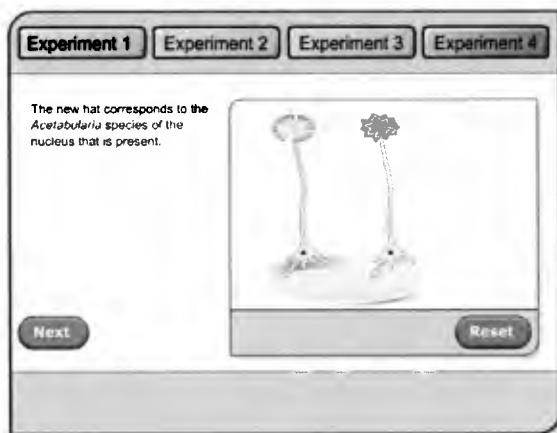
After each presentation of Hammerling's four experiments, multiple choice questions appear requiring students to draw conclusions from experimental evidence.

In the first experiment, the *Acetabularia* cell is cut into three sections. Only the tip and rhizoid develop a hat (Figure 1.3), leading to the conclusion that the tip and rhizoid may contain genetic material. In Experiment 2, the tip is removed, and the rhizoid is left attached for a few days. The rhizoid is then removed, and the stem develops a hat. The multiple choice questions following Experiment 2 lead to the idea of a chemical signal passing from rhizoid to tip, and that this must be chemical in nature. Experiment 3 allows students to transfer the nucleus from the rhizoid into the isolated stem, using manipulables of a scalpel and micropipette. The stem then develops a hat. Evidence from Experiment 3 supports the idea that it is the nucleus, not the rhizoid, which controls development.

Experiment 4 tests the idea that the nucleus controls development through chemical messengers using two different species of *Acetabularia*, with different shaped hats. The

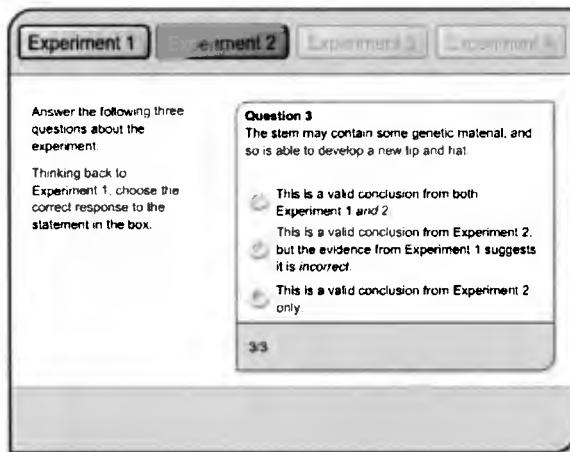
rhizoids are swapped between the species. At first an intermediate hat grows. When this is removed, a second hat develops which is characteristic of the species whose nucleus is present (Figure 1.4).

Figure 1.4 Animation after Experiment 4 in the tutorial



The multiple choice questions after each experiment are complex, requiring students to identify evidence which supports and refutes the conclusions (Figure 1.5).

Figure 1.5 Question following Experiment 2 in the tutorial



The final question in the tutorial asks students to link evidence from the two stages of Experiment 4 to three separate conclusions. It presents the idea that chemicals from the nucleus remain in the cytoplasm and affect development (Figure 1.6). This leads to an explanation for why an intermediate hat grows at first.

Figure 1.6 Final question after Experiment 4 in the tutorial

Experiment 4 was in two stages:

1. The stems were switched and an intermediate hat grew from the tip;
2. The hats were removed and a new hat corresponding to the species of the nucleus grew.

Type into the boxes the number of the stage (1 or 2) which you think provides evidence to support the following conclusions from Experiment 4:

the nucleus determines which hat develops

the cytoplasm contains chemical signals which influence hat development

the chemical signals present in the cytoplasm are determined by the nucleus

Submit

The stated purpose of the tutorial is:

- to encourage students to discuss the evidence and conclusions drawn from a set of experiments
- to appreciate the influence of the nucleus and cytoplasm on development.

In addition to these stated aims of the activity, students practise deductive skills, and apply scientific knowledge on the structure and function of genes and how genes control cell activities (protein synthesis).

1.7 Setting the research questions for study

Teachers and students received the SNAB course resources with enthusiasm. With some reservations relating to accessing hardware and a good internet connection, and integrating the electronic activities into a teaching sequence, the ICT tutorials were regarded as a positive asset. Despite this finding from the evaluation, I was still exercised with questions of how and why the ICT tutorials help students learn, and these questions underpin the central research questions in this thesis. Section 1.5 discussed how there is no commentary on the affordances of ICT from teachers, students or evaluator in the pilot study, which only sets out to describe the situation, not to suggest reasons or explanations.

The variety of different types of activity included in the SNAB ICT tutorials means that it is not useful to consider these tutorials all together, as a single category of resource. The medium of ICT may be less important than other characteristics of the activity, such as its intrinsic motivating challenge and the links it makes with other areas of study. An activity at

the computer does appear to motivate students, but this may be for a number of reasons, only some of which may relate to a computer's effectiveness as a learning tool.

It is important to know which particular aspects of ICT activities support effective learning. Educational design experiments should aim to develop generalised principles that can guide future developments. This idea underpins the initial research question of this study: *to what extent can generic principles frame educational design?*

The aim of the study is to establish the affordances of the generic principles in the Quintana *et al.* (2004) scaffolding design framework in guiding identification and analysis of features in the *Acetabularia* tutorial which support effective learning. The study uses empirical data providing evidence of learning and barriers to learning.

This thesis provides a detailed analysis of the role of a learning intervention, and explores what can be abstracted as general design principles. It goes beyond the type of analysis which is normally possible in an evaluation of a new resource.

The study explores the theories of learning and pedagogical models which are relevant to design of educational software. In a discussion of learning theories and scaffolding of learning in Chapter 2, an approach to this study is suggested, which sets out to analyse the cognitive demands of the SNAB tutorials, and the scaffolding which supports the tasks. The effect of learning materials and media on cognitive load, structuring of the content and providing feedback are linked to research in ICT-based and other intervention experiments. The nature of science inquiry in particular is discussed, in a consideration of the challenge of scaffolding learning in this domain.

Chapter 3 outlines the methodology used in this study, which aims to develop an approach to principled design using the Quintana *et al.* (2004) framework. Chapter 3 sets out a task model based on a decomposition of the tutorial. This is used in the initial analysis of data to identify evidence for learning and barriers to learning. By using a previously developed framework in the second stage of the analysis, this study seeks to contribute to the knowledge base of educational design, building on previous work that is relevant to the specific design being considered.

The data is presented in Chapter 4, organised according to the learning outcomes listed in the task decomposition of the tutorial carried out in Chapter 3. The data provides evidence of learning and barriers to learning, from which the effects of scaffolding in the tutorial are deduced. In Chapter 5, the framework is tested using the empirical data.

The findings are discussed in Chapter 6 in relation to their implications for the future development of the *Acetabularia* tutorial. This chapter also suggests some revisions to the framework which emerge from this study. Finally, Chapter 7 makes some suggestions for follow-up work, and provides some reflections on the study.

Chapter 2 Theories underpinning the study

2.1 Introduction

The scaffolding of complex tasks in science inquiry learning is a challenge for educational designers. Designers need to understand the processes of the domain, the relevant pedagogies to support learning, and the potential of software tools to carry out the necessary scaffolding. E-learning literature often makes claims to pedagogies, and teaching and learning approaches such as constructivism, communities of practice and collaboration (Conole *et al.*, 2004). If the development of software for learning is to be pedagogically driven, it is essential for educational designers, researchers and evaluators to be more explicit about how pedagogic principles apply to software.

Chapter 1 introduced the Quintana *et al.* (2004) framework, developed to guide scaffolding design in the specific domain of learning through science inquiry. This chapter reviews some learning theories which are relevant to guidance for designers and to interpreting the data from this study. Literature from the fields of inquiry learning and reasoning cited in the Quintana *et al.* (*ibid*) scaffolding design framework is discussed, along with other studies on learning and multimedia resources relevant to this specific study of learning through a classic inquiry.

The chapter starts with a discussion of how the literature on how students learn can be applied in the context of educational design (Section 2.2), building on the discussion of the knowledge base of educational design in the first chapter.

Section 2.3 follows with a description of what is understood by scaffolding learning, and how scaffolding approaches apply to learning in the domain of science inquiry. This section draws on ideas about apprenticeship and situated cognition to make the point that scaffolding needs to support learning that can be used to solve problems across a range of contexts.

Section 2.4 explores what the literature says about learning through science inquiry, leading to a discussion of the role of explanations as epistemic products of the discipline in Section 2.5. Section 2.5.2 and Section 2.5.3 review the writing on how science knowledge is constructed, including the role of mental models and students' misconceptions.

Section 2.6 sets out the different types of content to be learnt through science inquiry, and discusses how theories of situated cognition suggest the need for scaffolding to help students to resituate their knowledge in new contexts. Section 2.7 sets out the potential barriers to learning that are illuminated through the literature on cognitive load.

2.2 Applying knowledge about how students learn in educational design

Chapter 1 introduced a discussion on the generalisability of educational research, and its potential for producing practical impact through educational design (Section 1.2.2). Barrow (2005) argues that each educational situation is unique, so research can only depict a particular situation. Extensive research into ICT support for inquiry learning, for example, has not moved the main uses of technology in secondary level instruction beyond drill and practice, word processing, and web-surfing (Fishman *et al.*, 2004). Aiming to achieve demonstrable impact from educational research and educational design would require a refocusing onto the fundamental concerns of practitioners (Reeves, 2011).

A 2006 EPPI review of research into the effect of ICT activities in science lessons raises just this question about the potential applications of research. The review found no high quality evidence about the use of ICT to teach science ideas. This is despite the fact that evaluation studies which were not accepted for inclusion in the final review claimed that ICT, and simulation in particular, can be helpful in improving scientific knowledge and an understanding of the scientific approach (Hogarth *et al.*, 2006). This review reflected the need for more good quality research to compare the effect of different ICT teaching activities and the teacher support which makes them more effective. The challenge of applying educational research is exemplified here: the review shows how easy it is for educational designers to fall into approaches which ignore what is known about how students learn.

Paradigms of learning which embrace social constructivism alter the model from the traditional view of acquisition of knowledge to participants in learning communities. Learning resources from the constructivist model need to provide opportunities for discussion and feedback as well as communicating new ideas. This change in approach has shifted studies away from considering changes in students' knowledge states over time to studies of learning as a contextualised set of social practices (Kelly and Sezen, 2010). This has resulted in a shift in e-learning educational design from a focus on presenting the

content to an understanding of the importance of communication and collaboration between learners. Based on group learning theories, which suggest that small groups can learn as entities (Kasl and Elias, 2000), activities designed for collaboration are founded on epistemologies which see knowledge as a social construction.

The perspective of learning as a social activity, involving discussion and responsive feedback, suggests a tension for software designers: as a result of the considerable affordances of multi-media for 'showing' phenomena, it is easy for designers to fall back into a behaviourist view of learning as an automatic response to 'input' stimuli (Skinner, 1954).

Software designers also need to consider the evidence for promoting cooperative learning rather than learning carried out by individual students sitting at a computer. The rationale for encouraging social, cooperative learning experiences in science lessons is supported by a large number of studies which indicate that cooperation encourages higher achievement than competitive or individualistic activities (Slavin, 1990; Johnson, Johnson and Holubec, 1994; Tsay and Brady, 2010). Cooperative activities also tend to promote the development of higher order levels of thinking, essential communication skills, improved motivation, positive self esteem, social awareness and tolerance for individual differences (Johnson and Johnson, 1993).

Social constructivist theories suggest that software scaffolding should take the form of methods used to persuade students into new ways of seeing the world. This must involve experience, but also talking about experiences. Students need to be inducted into new ways of talking about phenomena as part of constructing new ideas. Social interaction brings about active processing through articulation of understanding, questioning, feedback and reflection on learning. It helps to position new knowledge in the context of learners' previous knowledge and experiences (Sutton, 1992).

Laurillard (2002) sets out the importance of discussion in her 'Conversational Framework' which describes the role of social interactions in pedagogical situations. The Conversational Framework is organised around four activities: discussion between the teacher and the learner; adaptation on the part of the learner and the teacher; interaction between the learner and the environment constructed by the teacher; and reflection on the feedback from learning activities by both teacher and learner. These suggested affordances of discussion and feedback resonate with Vygotsky's (1978) idea of keeping students in their zone of proximal development (ZPD) for learning to be maximised, discussed later in terms of the definition of scaffolding (Section 2.3).

If it is the case that learners benefit from social interaction with peers and experts, from active approaches to learning, and from maintaining their effort within their ZPD, educational designers must aim to develop classroom activities which encourage these experiences. This involves developing the type of task where students will consider the added effort of collaboration is worthwhile, rather than focusing on achieving a quick outcome (Schauble, Klopfer and Raghavan, 1991). More open tasks, problem solving, predicting and experimentation, along with less testing of simple recall, will increase higher level thinking as students engage in the tutorials.

Quintana *et al.*'s (2004) guidance is based on the premise that constructing and articulating an argument is a critical constituent of learning through science inquiry. Constructing an argument involves feedback, reviewing, reflecting on, and evaluating results, synthesising explanations and deciding where the weaknesses and strengths are in one's thinking (Collins and Brown, 1988 ; Davis and Linn, 2000; Loh *et al.*, 2001; Davis, 2004). Quintana *et al.*'s (2004) strategies show how it is possible to achieve some of the interactivity and adaptability implied by dialogic approaches through software tools. Scaffolding which uses the affordances of ICT to provide optional support and routes through the material, will allow more individualised support for students. For example, feedback can adapt to the answer given by a student and free text responses can be checked for key words or phrases so assessment items are not limited to multiple choice questions.

Section 7.6.2 argues that, as a result of the critique of the framework in this study, articulation and reflection are seen as core to process management and sense making, so it does not make sense to separate this as a category for consideration of scaffolding. Even so, the separate consideration of articulation and reflection during learning promotes the consideration of what the content of this should be, and how the focus of articulation should be guided through scaffolding. Suggested revisions to the SNAB tutorial discussed in Chapter 6, and Section 7.6.2 provide a more detailed discussion of how designers could consider what is discussed during inquiry and how software tutorials can encourage this important process.

A high level of adaptive feedback is a feature of effective teacher-pupil interaction, and even the most complex software programming does not replace the scaffolding function of teachers. Sandoval (2003) argues that software should not attempt to mimic the teacher-pupil relationship, but should aim to complement the teacher. Even so, designers should explore the potential of tools which mirror some aspects of the scaffolding carried out in the interactions between students and an expert teacher. Towards this purpose, this

chapter explores in more detail how science inquiry and scaffolding are defined in an educational context, what these involve and how scaffolding of learning in this domain can be achieved.

2.3 Scaffolding learning

2.3.1 Scaffolding as an educational metaphor

The definition of scaffolding in the online Oxford Dictionaries (2011) is:

A temporary structure on the outside of a building, made of wooden planks and metal poles, used by workmen while building, repairing, or cleaning the building.

The original use of the building metaphor 'scaffolding' in an educational context was by Wood *et al.* (1976), who saw this type of support as typical of a tutoring situation where the tutor knows the answer and the learner does not. The tutor controls the elements of the task that are beyond the learners' capacity, so the learner is working within their range of competency. The term scaffolding was never actually used by Vygotsky in this context, but it describes the process he articulated, where a more competent peer, parent or expert teacher supports learners to reach their full potential (Vygotsky, 1978).

Vygotsky's (1978) theories of learning highlight the role of discussion and feedback in helping students to make links with their prior learning. Central to Vygotsky's idea of learning are the interactions between students and an individual with expertise to be passed on. His concept of the 'zone of proximal development' (ZPD), describes the difference between what a learner can do without help and what they can do with assistance from an adult or capable peer.

The difference between what students can achieve alone and an intended learning outcome represents the gap which needs to be bridged by scaffolding, whether this is supported by a teacher, peer or software tools. 'Bridging', which means making connections between learners' intuitive understanding and more formal understandings of the discipline, is identified by Quintana *et al.* (2004) as a particular role for scaffolding.

Extending the scaffolding metaphor

Pedagogical techniques to support learning were discussed in terms of scaffolding from the early 1980s. For example, Scardamalia and Bereiter's (1983; 1985; 1987) research used procedural facilitation to support the use of more advanced writing strategies. The pedagogical underpinning of Scardamalia and Bereiter's use of facilitators relies on elements

of cognitive apprenticeship, discussed below (Section 2.3.2). These were physical note cards with lead-in components to sentences. They were designed to scaffold writing activities, through explicit models of more advanced forms of writing. Specifically they were found to help primary level pupils evaluate, diagnose, and revise their compositions effectively, independently of any other support.

The idea of scaffolding through this type of physical artefact extends the scaffolding metaphor beyond Wood's idea of an adult intervening as a child carries out a task. The notion of scaffolding has recently been applied even more broadly, to include features and functions of technology which supports learning (Sherin, Reiser and Edelson, 2004). Brush and Saye (2001), for example, describe scaffolding in terms of tools, strategies, and guides which support students in attaining a higher level of understanding than they would on their own.

The range of strategies used to scaffold learning includes questioning, explanation, cueing, coaching, feedback and corroboration. Reiser (2004) explains that scaffolds should provide structure to give learners a foothold on their work. This enables them to engage in previously inaccessible activity. Reiser also points out that scaffolds should avoid making work too easy. Scaffolding which problematises particular ideas may actually make learning more difficult in the short term, but in a way that is productive for learning. Problematising draws students' attention to important ideas and issues so they can internalise these aspects of the work (Sedighian, 2001; Reiser, 2002).

In a classroom situation, teachers provide scaffolding by continuously diagnosing learners' level of understanding and modifying the support given as a result of this diagnosis. The teacher aims to draw learners into new areas of exploration (Rogoff, 1990), while building on prior learning and keeping within the learners' zone of proximal development (ZPD). Just as physical scaffolding is removed once it is no longer needed, scaffolding for learning fades as students become more expert.

Reciprocal scaffolding is a term used for learners collaborating, learning from each other's experiences and knowledge as they work together on a task (Holton and Clark, 2006). Reciprocal scaffolding was acknowledged by Vygotsky, in his description of a 'more competent peer' providing assistance during learning (Vygotsky, 1978). In practice, a classroom situation will involve scaffolding from both teachers and peers, and this model of scaffolding is consistent with ideas of social constructivism discussed earlier, and the cognitive apprenticeship model proposed by Collins *et al.* (1989).

2.3.2 Apprenticeship as a model of scaffolded learning

Cognitive apprenticeship

Collins, Brown and Newman (1989) summarise the process of scaffolding as part of a teaching approach which they call cognitive apprenticeship:

When scaffolding is provided by a teacher, it involves the teacher in executing parts of the task that the student cannot yet manage. A requisite to such scaffolding is accurate diagnosis of the student's current skill level or difficulty and the availability of an intermediate step at the appropriate level of difficulty in carrying out the target activity. Fading involves the gradual removal of supports until students are on their own.

(Collins, Brown and Newman, 1989 p. 14)

Although their description of scaffolding appears to be teacher-led, Collins et al. (1991) acknowledge the role of the social context in which learning takes place. They describe cognitive apprenticeship as being embedded in a subculture, providing learners with continual access to models of expertise-in-use, and a range of learners with varying degrees of skill. Learners use these models to refine their own understanding.

In the development of their framework to guide designers of software scaffolding tools, Quintana et al. (2004) identified the needs of learners in terms of the cognitive tasks which they must carry out in the context of science inquiry learning. They focussed on approaches to reduce the cognitive complexity of tasks where learners encounter barriers. This resulted in a framework of scaffolding strategies which encompass a range of software tools and features, and which is grounded in pedagogical support rather than technology.

Work-based apprenticeship

Collin et al.'s (1989) pedagogic model of cognitive apprenticeship draws on the idea of traditional workplace apprenticeship, where a novice works alongside an expert. Work-place apprenticeship settings provide opportunities for novices to participate in tasks that lead to the overall goals of the setting. An apprentice is allocated an experienced practitioner, and learning a specific task takes place though working alongside the expert. Apprenticeship involves informal learning in a problem solving, applied situation, but tasks are restricted to make them manageable as the apprentice learns (Lave and Wenger, 1991). The later analysis in Chapter 5 identifies restricting tasks as a role of scaffolding in the *Acetabularia* tutorial.

As in a workplace apprenticeship, cognitive apprenticeship must scaffold learning through deliberate practice. Cognitive skills and strategies must be modelled over time, and learners supported as they engage in tasks which apply these skills.

Both tacit learning and explicit learning of the concepts and practices of the workplace take place through experiencing the complex work environment while being guided by the instructor (Barab and Hay, 2001). In tacit learning, the teacher and student may not be aware of the learning taking place. For example, the apprentice tailors described by Lave and Wenger (1991) were allowed to iron finished garments. This restricted task tacitly taught them about cutting and sewing. Explicit learning, by contrast, is usually planned, acknowledged and articulated by the learner and teacher. One of the challenges in learning science is that knowledge of processes of the discipline are typically tacit for experts. As a result, instruction often fails to make these strategies explicit to learners (Reiser, 2004).

Learning through science inquiry involves aspects of cognitive apprenticeship as students develop and apply cognitive tools in an authentic domain. This type of learning relies on a task that engages the learner but involves elements still to be mastered (Brown, Collins and Duguid, 1989).

Designing scaffolding at the appropriate level

Designers of scaffolding for inquiry have to make decisions on the level of challenge for learners in the context of problem solving. These decisions can usefully draw on the literature on the efficacy of problem-based learning with reference to the audience of the materials being designed. An implication of this literature is that instructional materials must be tailored to changing levels of learner expertise (Kalyuga, 2008).

Decomposing the task which learners are involved in is a crucial first stage in identifying what needs to be made explicit through scaffolding. For example, Scardamalia and Bereiter's (1987) use of facilitators to scaffold writing, discussed in the previous section, provides an explicit strategy for improving pupils' compositions through scaffolding individual components of writing.

Learning tasks must be challenging enough to maintain the learner's interest, while the teacher gauges the level of scaffolding needed to manage frustration (Wood, Bruner and Ross, 1978). By definition, scaffolding reduces the learners' freedom to choose an approach. It aims to avoid unproductive paths while encouraging higher level skills and problem-

solving strategies. As a learner becomes more expert, the scaffolding fades, and learners take increasing responsibility (Collins, Brown and Newman, 1989).

The complementary roles of teacher and scaffolding are suggested in this discussion through consideration of the adaptive potential of teachers, who can gauge levels of scaffolding needed and fade appropriately. On the other hand, in a busy classroom environment, where there are many demands on a teacher's time, the potential for tools which can offer a more restricted but immediate selection of strategies and guidance is important. Tools which have the capability to move the majority of students on in their learning could reduce the number of students needing attention at any moment, allowing fewer but richer, more individualised and more effective teacher-pupil interactions.

Recent studies have demonstrated the significance of the level of learner expertise for the choice of instructional methods. Approaches which are effective for novice learners become ineffective or even harmful as learners gain expertise. The effect is reversed, with approaches that are effective for experts being harmful for less expert learners. This expertise reversal effect was demonstrated across a range of instructional techniques, including embedding textual explanations into diagrams to reduce learner split attention (see Section 2.7) using synchronised verbal commentaries along with animated diagrams and providing learners with worked examples (Kalyuga et al., 2001; Kalyuga et al., 2003; Kalyuga, 2008).

Problem solving, for example, has been shown to be an ineffective pedagogic approach for inexpert learners, inhibiting learning of the significant aspects of the problem's structure. Approaches which use worked examples that take students through the steps of a solution have been found to be superior to complex problem-solving when learners are inexpert. As learner expertise increases, worked examples become redundant and problem solving is then more effective for learning (Kalyuga et al., 2001). Chapter 5 suggests that the *Acetabularia* tutorial uses the idea of partially worked examples in the multiple choice questions (see section on apprenticeship learning p.164).

These expertise reversal effects can be explained with reference to previously discussed ideas of making strategies explicit to learners (Reiser, 2002) as part of cognitive apprenticeship (Collins, Brown and Newman, 1989). They have also been explained within the framework of cognitive load theory (Chi et al., 1994; Van Merriënboer and Sweller, 2005). Cognitive load theory refers to the inhibitory effect on learning that complex tasks

can have due to the limitations of human cognitive architecture. It is explained in more detail in Section 2.7.

So far, this chapter has discussed how learning is often situated in an application of skills or concepts which is specific to a professional community. In the apprenticeship model of learning, new knowledge and understanding are learnt in the most likely contexts for their application in future problem solving. For learning to take place through apprenticeship, it must be scaffolded by an expert teacher.

What links these ideas of scaffolding, collaborative learning and apprenticeship together is a view of learning as a socially constructed activity, involving individuals in active processing of new information in relation to prior learning. This model of learning explains how interactions with experts and peers provide opportunities for an individual to demonstrate or articulate their views. This enables the individual's understanding to be compared with others', and to be challenged, tested or refined through these interactions.

Where learning science deviates from the apprenticeship model is that the established theories used by scientists to explain observed phenomena can't usually be learnt through experience of these phenomena in the way that processes and skills can be learnt through practice. Learning science also deviates from apprenticeship as students are often expected to resituate learning by applying it in new contexts. If students' learning can only be applied in the precise context in which it was learnt, it may be of little use for future problem solving. Evidence from this study suggests that resituating prior knowledge is a major challenge to students, who do not draw on the relevant ideas which could help them to explain the Hammerling experiments. Establishing the background science ideas needed to make sense of a contextualised problem involves making links with previous experience of these ideas. The next section discusses the challenge of learning through science inquiry. Resituating learning into a new context is discussed later, in Section 2.6.

2.4 Learning through science inquiry

2.4.1 Developing scientific knowledge and skills

Wood (1976) stated that an effective tutor must have a theory of the task or problem which learners engage in, and how it may be completed. The tutor must also have an understanding of the tutee's abilities in the relevant knowledge and skills. Both these are needed for the tutor to generate feedback and to devise appropriate feedback situations. Effective instruction is, then, dependent on both the task and the tutee. It must follow that

knowledge of science education and specifically learning through science inquiry are prerequisites of successful scaffolding of learning in this domain.

Science education is a special case in terms of learning. Scientific knowledge, which underpins the content and pedagogy of science education, often requires considerable intellectual effort. An explanation which eventually becomes accepted by the scientific community forms an 'ontological entity' which is unlikely to be arrived at by individuals observing the natural world. The implication of this for science education is that students need to be initiated into the socially constructed ideas and practices of the scientific community. Specifically, students must make their own sense of the way that scientific knowledge is constructed and validated, rather than constructing their own knowledge from empirical observations (Driver *et al.*, 1994). This reflects Bruner's (1999) argument that we should teach the structure of a subject and processes of the discipline along with its concepts. It also suggests scientific theories should be taught explicitly rather than expecting students to discover these for themselves.

This study of scaffolding learning through science inquiry draws on a definition of inquiry from Quintana *et al.* (2004) which in turn is consistent with notions of science inquiry learning from the literature:

... we define science inquiry as the process of posing questions and investigating them with empirical data, either through direct manipulation of variables via experiments or constructing comparisons using existing data sets.

(Quintana *et al.*, 2004, p. 341)

This definition refers to what professional scientists do, and is independent of the discussion of the needs of science students learning through science inquiry as suggested by theorists such as Driver and Bruner. Quintana *et al.*'s (*ibid*) scaffolding design framework goes on to provide strategies to support the processes needed for students to take part in and make sense of an inquiry.

2.4.2 The educational purpose of science inquiry

Scientific inquiry is not an end in itself in an educational context. It is the method used to develop the ideas and explanations which form the body of accepted scientific knowledge. Inquiry is important in teaching science because it draws attention to phenomena of interest, encouraging students to develop links between their observations and a scientific way of thinking about these observations. This method is particularly useful where students are unlikely to have noticed the phenomena themselves, or to have observed and analysed

phenomena in sufficient detail in their everyday lives. The educational purpose of the inquiry can be seen as saying 'see it my way' (Ogborn et al., 1996, p. 18), in a world where science narratives are far from common sense.

Wells (2008) supports inquiry as a route to understanding science. His description of learning through science inquiry can be interpreted in terms of collaborative inquiry, situated learning⁵ and scaffolding, so inquiry acts as the key element in creating a community of learners. Wells argues that discourse as part of inquiry is necessary to move on conceptual understanding, and only when students have carried out their own inquiries do they become willing and able to engage in the necessary discourses.

The type of task which students engage in is central to learning. Vygotsky (1978) suggested the teaching of writing should be organised through tasks which create a necessity for the writing. Using the same principle, teaching of scientific concepts should make sure that the application of the concepts is incorporated into a task that is authentic to the domain. Science inquiry provides just these situations, where scientific concepts function as tools for solving a problem.

Section 2.3.2 discussed the use of authentic inquiry tasks in the apprenticeship model of learning. The use of the term 'authentic' to describe the tasks that students take part in as they carry out the *Acetabularia* tutorial requires some problematising. The *Acetabularia* tutorial situates learning about development in the context of Hammerling's classic experiments on a single-celled alga. While it would not be disputed that Hammerling took part in an authentic scientific inquiry, the extent to which the tasks in the SNAB tutorial are authentic is less clear.

The tutorial encourages discourse through collaborative problem-solving, and scaffolds learning through structuring the problem and prompting students' thinking using multiple choice questions. While students are not taking part in a full inquiry in the sense that Hammerling did, they do take part in a cleaned-up and restricted version⁶ of some of the tasks which Hammerling would have to engage in. For example, linking the evidence from the experiments to conclusions is an authentic reasoning task which contributed to Hammerling's inquiry. 'Authentic' is used here in the sense that the tutorial sets out a

⁵ Situated learning refers to learning within a specific context such as a professional community.

⁶ An account of a classic inquiry does not usually refer to the numerous failed experiments, dead-ends and repetitions which are part of a professional scientist's work.

genuine problem which was tackled by scientists in the past: how is development controlled? The use of classic experiments for teaching purposes acknowledges that this approach uses versions of science inquiry specifically designed and adapted for learning. This does not involve students in discovering scientific concepts, but it can involve them in aspects of some tasks which are authentic to the domain.

2.4.3 The content to be learnt through science inquiry

The vocabulary for types of curriculum content

It is worth mentioning here, as an aside, that in discussing curriculum content, the issue arises of the lack of a consistent approach to the available vocabulary. This chapter refers to ideas, concepts, processes and now skills. Gagné (1992) defined a set of domain-free 'learned capabilities', including intellectual skills, cognitive skills, verbal information, attitudes and motor skills. Tiberghien (2000) characterises the domain of 'objects and observables' and a second domain of 'ideas'. The American 'Benchmarks Online' curriculum document (AAAS, 2009) refers to 'Habits of mind' that students of science should aspire to. These include Values and Attitudes, Manipulation and Observation, Communication Skills and Critical-Response Skills. Other authors list the inquiry and problem-solving skills needed for independent working in science (Biological Science Curriculum Studies, 1993; BSCS, 1993; Reif and Scott, 1999; Schneider et al., 2002; OECD, 2006) and the more generic thinking and learning skills which are needed across domains (Campbell et al., 2000; Spektor-Levy, Eylon and Scherz, 2008). Recent UK changes to the 14-19 curriculum have emphasised transferable skills relevant to study and employment. The 11-14 secondary curriculum in England and Wales from 2008 identifies 'personal, learning and thinking skills' (QCA, 2008) as part of the holistic learning experience.

These references all assume that a common set of learning characteristics apply across learning tasks, but there is more work to be done in characterising an agreed vocabulary for describing the content. By restricting the decomposition of the *Acetabularia* tutorial to three categories of content (background science ideas, contextual science ideas and science inquiry processes), this study acknowledges there will be some consistency and overlap with other writing about science curriculum content, but that these categories are not exhaustive or necessarily the only ones that are useful in this context.

Educational outcomes of science inquiry

The intended educational outcomes of a specific inquiry are rarely limited to the context of the inquiry. Where learning science concepts is an intended learning outcome, students are

expected to resituate knowledge and understanding to explain similar phenomena in different contexts, particularly in advanced level study. Scaffolding needs to ensure that inquiry serves to exemplify how the big, overarching principles in science play out in a range of contexts (see Section 2.5.2).

For example, learning about the role of the nucleus in the SNAB *Acetabularia* tutorial aims to support understanding about how a human embryo develops from a fertilised egg cell. This learning can be applied to all eukaryotic cells. To miss this point misses the significance of Hammerling's inquiry and the significance of choosing *Acetabularia* for the subject of study, as a single cell large enough to dissect and manipulate.

Students are also expected to learn and apply the processes of science inquiry. The need to convey both a body of knowledge that has been built up over many years of scientific practice, and knowledge about the process of scientific inquiry itself results in a fundamental tension in learning through science inquiry. Layton (1973) argues that reconciling these two objectives of science education simultaneously is unachievable. He suggests that process should be attended to as a separate objective, alongside background science content.

The domains of science concepts and inquiry processes are, though, inextricably linked. Separating these as part of a pedagogic approach to learning science through inquiry simply may not be possible. Millar (2004), for example, argues that a science inquiry does not make sense without the context of the scientific theories which it aims to test.

The pedagogic solution may lie between these two positions. It is clear that the relevant processes and scientific concepts can be developed independently of the inquiry. For example, understanding the role of the nucleus can be taught separately from the *Acetabularia* inquiry, as can the concept of the controlled experiment or empirical evidence. Layton (1973) makes the point that any pedagogical task can potentially be decomposed and each separate element can be addressed individually. This does not preclude Millar's (2004) argument, as once learning is situated in a specific inquiry context, the processes of inquiry become embedded within this context.

This discussion leads to the conclusion that different levels of scaffolding are needed at different stages in a learner's progression. An inexpert learner needs the structure provided by separating out the elements involved in an inquiry, while a more expert learner can integrate processes and knowledge in a more sophisticated task model of science inquiry.

Practical inquiry can give students experience of identifying and making links between these two domains of knowledge. In a learning situation rather than a professional research situation, students need expert guidance to help them make links between the data and the scientific theories which explain them. It could be argued that students rarely take part in genuine inquiry in the sense that professional scientists do, as the knowledge outcomes in school science inquiry learning are foreclosed. However, as they develop scientific expertise and knowledge, students can take part in aspects of science inquiry tasks that are themselves genuine to the domain.

The suggestion that the way practical inquiry is often enacted in schools is not authentic is not new: Hodson (1996) traced the changing nature of science inquiry in schools from the 1960s to the present. He argues that discovery learning, process approaches, and other movements which apply aspects of constructivist pedagogy have all misrepresented the nature of professional science inquiry.

School practical work frequently presents situations as inquiry which actually have a learning aim of understanding of scientific concepts that students could not possibly deduce from an experiment (Abrahams and Millar, 2008). In contrast, authentic inquiry involves a process which leads from an open question or problem. It is also framed by an expert scientist's informed predictions based on their prior knowledge.

Where science inquiry is used for learning with inexpert students, integrating scientific theories is a pedagogic problem which has not yet been solved. Chapter 5 continues this discussion on the extent to which science inquiry learning is authentic, in the context of apprenticing students in the processes of the discipline.

The challenge of designing strategies for supporting students in science inquiry centres on the balance between and the integration of the two objectives described by Layton (1973). This study suggests that Quintana *et al.*'s (2004) scaffolding design framework does not entirely succeed in this task.

Science inquiry approaches

If, as described above, science inquiry learning attempts to model the investigative activities of professional researchers, there may be an implicit expectation that students 'rediscover' fundamental scientific concepts (Kirschner, Sweller and Clark, 2006, p. 3). Inquiry learning is pedagogically equivalent in many aspects to approaches called by names such as experiential learning (Ogborn *et al.*, 1996), discovery learning (Kirschner, Sweller and Clark, 2006),

problem-based learning (Boud, Keogh and Walker, 1985) and constructivist learning (Bruner, 1961). What these approaches have in common with each other, is an emphasis on learners constructing knowledge for themselves rather than being presented with it (Barrows and Tamblyn, 1980). How they differ is in the amount of scaffolding that is considered necessary to bring about learning (see Section 2.3). Discovery learning, for example, is associated with minimal guidance, where problem-based and inquiry learning can provide extensive scaffolding to support learning (Mayer, 2004).

In their failure to make explicit how background science ideas should be introduced, approaches to science inquiry learning frequently imply an inductivist rather than a hypothetico-deductive approach to the link between evidence and explanation. Most mainstream philosophers of science describe a hypothetico-deductive view of scientific reasoning, where evidence from observations lead to conjectures or hypotheses aiming to explain the observations. Hypotheses allow specific predictions to be made, and these can be tested against the data. Through testing predictions from hypotheses against data from experiments, scientists become more or less confident in the hypotheses and the explanations of the world which they represent (Millar, 2004).

In practice, students are unlikely to 'rediscover' knowledge if 'shown' the evidence, as ideas and explanations do not emerge automatically from data (*ibid*). An inductivist view of inquiry learning points to lack of clarity between learning about the discipline and scientific research carried out by professional experts. Hypothetico-deductive approaches in science inquiry learning make a clear distinction between evidence and explanations and accept that inexpert students can't be expected to suggest hypotheses which draw on information not available from the empirical evidence (Giere, 1991).

Sutton (1992) suggests that the model of 'learning through doing' puts unreasonable expectations on tasks such as practical work. However, Hmelo-Silver *et al.* (2007) argue that studies which assert that problem-based or inquiry-based learning does 'not work' are asking the wrong question. If learning is considered holistically, these methods have been shown to develop deep and meaningful learning along with 'soft skills' such as research and communication. The more important questions are around the type of support and guidance which is needed to make these approaches effective.

'Doing' science will not lead to learning or using scientific concepts unless teachers provide scaffolding to help students to see the phenomena in the same scientific way that a professional might (Abrahams and Millar, 2008). It is important that the process of science

inquiry, based on the epistemology of the discipline, does not become confused with the pedagogy of inquiry learning.

It is also important to consider whether teachers' own understandings of the epistemology of science inquiry is based on an authentic model of how professional science works. If teachers see inquiry as essentially an inductive process where theories emerge from evidence, then their pedagogic approaches to learning through science inquiry will be centred in this epistemology. Windschitl *et al.* (2008) suggest that school science is based on a cultural lore of what scientists actually do. The basis of this is a flawed view of a universal scientific method which gives an unproblematic view of science and an oversimplified view of reasoning. This view promotes, for example, the idea of controlled experiments as the only method of generating data.

Millar (2004) points out that science education is fundamentally an act of communication of scientific knowledge rather than discovery. Practical work and simulations of practical experiments may have a role alongside the other modes of communication that teachers use. Handling and manipulating real objects and materials during practical work is an act of 'showing' which complements the 'telling' of teacher talk (Layton, 1973).

This view of practical work also applies to learning through classic inquiries such as the Hammerling experiments. The *Acetabularia* tutorial can 'show' students the processes of science inquiry, for example noticing what is significant in the data. It can also show how the scientific theories play out in the context of explaining development in *Acetabularia*.

For the purpose of this study, the literature suggests that a focus on both the approach to scientific inquiry and the way in which it is scaffolded are essential for effective design of supporting resources.

2.5 Developing scientific ideas

2.5.1 Developing explanations

The previous section highlighted a view that, by drawing on an inductivist paradigm of scientific inquiry, pedagogic approaches to constructing explanations as part of inquiry are confused. Scientific explanations are one of the products of science inquiry. The importance of science explanations is their role in illuminating phenomena. Explanations go beyond the data to make inferences and connections, to build scientific theories or models (defined in Section 2.5.3) which work. The models or theories can, in turn, be referred to when

predicting future events and to explain previously unexamined data (Wiggins and McTighe, 1999).

Explanations may be in the form of concrete scientific models, diagrams and terms or may be descriptions of more abstract concepts such as 'development'. In the science classroom, each of these types of explanations has the role of constructing entities on which future explanations are based (Ogborn *et al.*, 1996).

Sandoval (2003) suggests that, even with prompting, students do not necessarily have the epistemic knowledge to recognise what is significant in data, or to use data to build explanations. Leach and Scott (1999) also point out that, when students draw on scientific theories to explain data, they do not necessarily recognise the epistemological idea of using scientific models to explain a broad range of phenomena. An explanation then becomes isolated within the context in which it was learnt, as described by Lave and Wenger (1991) in their discussion of situated cognition in apprenticeship learning (see Section 2.3.2).

Problems students have in developing explanations may also be due to ontological barriers, where students lack a deep understanding of the scientific entities which are acting in the inquiry. The data in this study shows that students are confused about what *Acetabularia* is. This illustrates how students are not necessarily aware of the difference between the models and theories which they hold and the models and theories they need to develop through inquiry learning. This learning gap, which must be bridged through scaffolding, is the driver for producing explanations in science lessons (Ogborn *et al.*, 1996).

This thesis suggests that an ontological problem shown by SNAB students, leading from their difficulties in recognising what *Acetabularia* is, results in a failure to interpret Hammerling's experiments at a level of causation. Students can't draw on prior learning about cells and genes to make sense of the inquiry as it proceeds. It could be argued that the ontological issue causes an epistemological problem. It prevents development of a consistent, overarching principle involving cells and development to make sense of the data.

This example from the study of the *Acetabularia* tutorial illustrates how robust mental models of the entities acting in an inquiry are key to the construction of explanations, reinforcing Kuhn's (1989) argument that theory and evidence must be coordinated in the practice of developing science knowledge. Previous studies support the idea that generating explanations can lead to deeper understanding of new material (Kuhn, 2004). By scaffolding epistemically appropriate practices, the strategies which Quintana *et al.* (2004) suggest in their framework could support this type of cognitively productive activity.

Ogborn *et al.*'s (1996) model of explanations as nested entities which contribute to the big overarching stories of science suggests a pedagogic approach which explicitly develops these big stories. Section 2.6.1, later in this chapter, considers the challenge for students in resituating their learning to a new context. By considering how separate elements of science knowledge contribute to bigger explanations or 'stories', students' understanding of science will go beyond the contexts in which it was learnt, and will become more coherent as links are made with a wider range of phenomena.

2.5.2 The big stories in science

This discussion of the connectedness of knowledge reflects Ausubel's (1968) distinction between 'meaningful' learning, characterised by the development of strongly hierarchical frameworks of concepts, and 'rote' learning, characterised by the random memorisation of isolated pieces of information. Cognitive theories of learning acknowledge the active role of students during learning, as they process, organise and store new information. Constructivist theories explain that new information is most easily organised when links can be made with prior learning. 'Constructing' learning involves organising knowledge into mental structures called 'schemas', which are then refined to incorporate new knowledge (Anderson *et al.*, 1977).

Studies which have found that ideas students have about science are often piecemeal and disconnected make it clear that students need support to construct coherent learning (White, 1994; Wandersee, Fisher and Moody, 2000; Venville, Gribble and Donovan, 2004). Piecemeal understanding brings problems such as failure to use knowledge of physical science concepts to underpin biological concepts. For example, Berthelsen (1999) found that students do not relate water, a liquid, and carbon dioxide, an invisible gas, to the growing mass of a seedling. Students have often not made the connection between understanding of genetics concepts and concepts of living things. Their understanding of the gene may see its function and even location within the body as completely unconnected to DNA (Venville, Gribble and Donovan, 2004). These findings are reflected in the data from this study, which shows that students do not make links between development in *Acetabularia* and understanding of the action of genes from their previous study of inheritance.

Bloom (1981) recognised the challenge of developing coherent frameworks for knowledge, and urged teachers to identify abstractions which represent the basic ideas of a domain. He suggested that these abstractions can be used in a variety of problem-solving situations and

can help learners to make links between previously unconnected items of knowledge. Big, overarching ideas also provide a framework which helps learners to prioritise what they pay attention to. For example, if students carrying out the *Acetabularia* tutorial frame their sense-making in terms of the genetic code, they will be alerted to the idea that the nucleus produces chemicals which control cell functions.

The design challenge of the ‘Big Ideas’ paradigm

Linn and Hsi (2000) recommend that all learning in science education should explicitly contribute towards ‘big ideas’. Their idea of how new ideas are added and connections made between them to build more and more powerful and useful pragmatic scientific principles is the basis of their knowledge integration paradigm. This paradigm underpins the Design Principles Database (DPD) (Sinclaire, 2003) project at the *Center for Innovative Learning Technologies, Stanford University*. The project developed a web-based interface to give access to a set of interconnected design features and principles for learning technologies across all domains. Designs underpinned by the knowledge integration perspective encourage learners to make connections between existing ideas: to develop a knowledge web rather than simply adding to an incoherent repertoire containing potentially conflicting ideas (Eylon and Linn, 1988; Slotta, Chi and Joram, 1995).

The design challenge implied by knowledge integration is based on the understanding that big ideas may not be obvious to learners in the way they are to experts. Designers must bring the big ideas to life through activities which require students to consider these ideas in action (Wiggins and McTighe, 1999). As discussed later in this chapter in the context of situated learning (Section 2.6.1), knowledge is most effectively established when learning is based around authentic challenges in the domain. Authentic problem-solving tasks demand abstraction, resituation and application of the big ideas. They tease out the way scientists look at the world and solve problems that relate to the domain (Brown, Collins and Duguid, 1989). If tasks can be completed by merely following directions and using recall and logic, there will be little or no resituating of knowledge, so no prioritising of the big ideas.

The role of narrative in articulating the ‘Big Ideas’

Walter Fischer (1989), in his ‘Narrative Paradigm’ theory, suggests that all meaningful communication is a form of storytelling, and that human beings ‘experience and comprehend life as a series of ongoing narratives, each with its own conflicts, characters, beginnings, middles and ends’ (p. 57). Graesser *et al.* argue that narrative has a privileged status among various types of discourse:

The situations and episodes in narrative have a close correspondence to everyday experiences, so the comprehension mechanisms are much more natural than those recruited during the comprehension of other discourse genres such as argumentation, expository text, and logical reasoning.

(Graesser, Olde and Klettke, 2002, p. 2)

Wiggins and McTighe (1999) point out that interpretation of phenomena 'traffics in powerful stories, not abstract theories' (p.88). Other authors support this idea that the big ideas of science should be introduced as 'stories' or 'narratives'. Ogborn *et al.* (1996) argue that science knowledge can be reworked into story-like forms, not merely to add to its 'liveliness' or 'interest', and not merely to show it 'applied' to some real context, but more fundamentally to act as an involving, memorable and efficient knowledge carrier. Human beings are extremely good at retaining and recalling narratives rather than logical (but non-narrative) sequences of information. The overall structure and sequence of a narrative acts as a memory aid to the content. Too often, science narrative is broken down to examine the detailed elements, without being reconstructed so the big picture is seen clearly (Ogborn *et al.*, 1996).

Conant (1947) took an alternative view of the role of narrative, embedding science explanations in the narratives of storylines about the life of historic scientists. In this way Conant's approach supported understanding of the nature of scientific reasoning along with the science concepts. Solomon (2002) also recommended historic stories about scientists for the purpose of introducing elements such as ethical discussion in addition to motivating pupils. The *Acetabularia* tutorial follows this approach, by embedding the science within the narrative of a historic inquiry rather than making the science explanation itself the narrative.

Norris *et al.* (2005) point out that the effect on learning science explanations through narratives is unknown and difficult to test. Although there is empirical evidence favourably comparing, for example, comprehension after reading narrative and expository texts (Graesser, Golding and Long, 1991; Voss, Wiley and Sandak, 1999), to establish a narrative effect scientifically, the genre of texts would have to be kept the same in an experimental situation, while keeping all other factors the same. As narrative texts tend to be less complex in terms of vocabulary and density of information, Norris *et al.* (2005) suggest that such an experiment would be virtually impossible.

Norris *et al.* (2005) also distinguish between narratives which embody explanations that are intrinsic to science, such as explanations of natural phenomena, and extrinsic explanations. The latter would include the story of how Hammerling went about his classic inquiry and

the former an account of how genes control development. Distinguishing between these two types of explanation is not always straightforward. In the example of the *Acetabularia* tutorial, the narrative of the inquiry process drives the learning, but this is inextricably tied in with the emergence of the scientific theories about the control of development. Hammerling's explanations for each stage of his inquiry drive the next stages which test the emerging model.

The data from this study showed that, after carrying out the *Acetabularia* tutorial, SNAB students could describe the process of transcription and translation (an intrinsic explanation), and they could also describe events of the Hammerling experiments (the extrinsic explanation) (see data in Section 4.2.3: post interview data and experiment planning from Question 6). But they could not integrate the narrative of transcription and translation as part of the bigger story of development in *Acetabularia*.

Constructivist theories explain that students construct knowledge through active processing of new information, which interacts with their existing schemas. These theories argue against presenting pre-packaged interpretations. Using this constructivist paradigm, Wiggins *et al.* (1999) suggest that students should be allowed to form their own narratives. Even when there is a widely accepted construct such as evolution, students should be allowed to work through the issues themselves.

'Working though the issues' (Wiggins and McTighe, 1999, p. 92) need not assume that students can 'rediscover' the scientific theories which have taken professional scientists many years to develop. The stories of science should be told, and understanding constructed through activities which require students to build these stories as they interpret phenomena. Science inquiry learning needs to develop pedagogies for 'telling' the science stories which explain observations and data. Inquiry for learning can then be driven by the questions which students articulate about these phenomena in the context of specific science stories.

Solomon (1999) supports this idea, by suggesting that meaning making which draws on background science theories is most effective if it takes place as data emerge from an inquiry rather than before or afterwards. Solomon's studies also reinforce the idea discussed in Section 2.5.1, that coordinating evidence and theories is key to scaffolding inquiry learning.

Quintana *et al.*'s (2004) framework, described in Chapter 1 (Section 1.3) suggests scaffolding strategies which prompt students to articulate their understanding as they

develop explanations. However, it falls short of suggesting how to scaffold the construction of the big stories which apply across a range of inquiry contexts.

2.5.3 Construction of mental models

Science explanations draw on theories and models which represent scientific knowledge. A scientific theory is taken here to include concepts and abstractions of phenomena along with their quantifiable properties, and the quantitative laws that express relationships between observed variables (Merriam-Webster, 2011). Scientific models are a sub-set of scientific theories, as abstractions of the theories which allows these to be shared and discussed.

Suitable activities allow students to gain first-hand experience of applying these concepts and models to assist their knowledge construction. Scientific models are presented to students as part of the 'telling' of stories of science described in the previous section. In software tutorials the story is frequently 'told' using mixed media, including text, visuals, video and animation.

The role of visuals in communicating scientific theories

The visual organisers exemplified in the Quintana *et al.* (2004) framework and animations such as the manipulables in the *Acetabularia* tutorial, are constructed around a visual diagram or model which represents a scientific entity or complex concept in the inquiry. The data from this study of the *Acetabularia* tutorial suggests that careful attention to the representations in visuals is crucial in software design.

Scaffolding strategy 1b, 'Use descriptions of complex concepts that build on learners' intuitive ideas', draws attention to the importance of scientific formalisms in sense making. The visuals in software tutorials (and other science learning resources) often make assumptions about students' familiarity with the semiotics of the discipline. To bridge learners' understanding, designers should use visuals and signs that anchor constructs in learners' prior understanding (Quintana *et al.*, 2004). Interpreting scientific visuals such as those used in the *Acetabularia* tutorial involves knowing about the conventions being used in formal representations, and having skills in decoding them appropriately (Lowe, 1990).

The implications of research on visual literacy have been studied less in the context of science education than the comprehension of textual and linguistic information. Visuals require more attention for processing compared with text, because all the information is presented together, rather than sequentially. Visuals can, though, describe spatial features of

scientific objects which are not effectively communicated in text. Dynamic models and simulations can provide sequential information and, as a result, provide greater cognitive affordances for learners, even if more processing is required than text and still visuals (Gobert, 2005).

Acquiring information from visual sources depends on prior domain-specific knowledge (Brewer et al. 1984). Gobert (1999), for example, showed that domain experts performance better in tasks involving interpreting visual information, in a study of understanding a building from its plans.

Content depicted in scientific visuals uses a host of specialised graphic conventions, so students need to be apprenticed in interpreting these formalisms of the discipline (Lowe, 1990). Teaching models and educational designs interpret formal scientific representations further, through selection of particular expressions of meaning in the context being communicated. In this way, educational diagrams are outward evidence of the intentions of the teacher or designer (Kress et al., 2001). Gilbert et al. (2000) also point to the need for educational resources to cue important features for learners to attend to. They suggest that moving between the various models (2-D, 3-D, mathematical models) and their levels of representation from micro to macro, is something that students find difficult. It can't be assumed that students are familiar with all the conventions used in science teaching models and representations. The need for support as students interpret scientific formalisms and the intentions of educational visuals and models adds a layer of scaffolding beyond the guidelines in the Quintana et al. (2004) framework.

The diagram of *Acetabularia* used in the tutorial is a formalism which follows conventions which manipulate and distort reality. The alga is represented using a line drawing cross section of the alga, although the depiction of the hat is three-dimensional rather than sectional. Communication of the important aspects of *Acetabularia* uses signs suitable for the particular audience. The diagram is intended to communicate that *Acetabularia* is a cell, and that it has specialised parts. A photograph or drawing of the alga would not have done this as effectively: the nucleus, signalling that this is a cell, and central in the tutorial's narrative about development, would not have been visible in realistic representations or photos. On the other hand, a life-like representation or photograph might communicate information about *Acetabularia* as a whole organism.

Seeing *Acetabularia* as a cell

The data from this study shows that students refer alternately to *Acetabularia* as a 'cell', 'plant' and 'alga' throughout the tutorial (See data in Section 4.2.2). Chapter 5 (Section 5.3.1) suggests that the way students 'see' *Acetabularia* is likely to affect the background science ideas they draw upon to make sense of their observations.

The term 'seeing' is often used as a metaphor for comprehension. According to Gestalt⁷ theory, seeing in this sense involves prior experience and active sense-making about what is there. Ausubel (1968) theorises about how students learn from verbal and textual presentations. He supports the cognitive model of learning which underpins constructivism, arguing that learning relies on subsuming new material and relating it to relevant ideas in existing schemas.

Representations are a means of 'organising, inscribing, and containing meaning' (Giroux, 1992, p. 244). The literature on visual literacy points to the complexity of scientific formalisms and the expert skills needed to interpret them. For students to make sense of scientific representations, they need to process the information based on their existing knowledge, in the same way that interpreting any form of information relies on previous conceptual knowledge (Ausubel, 1968; Schönborn and Anderson, 2006).

Prior learning also determines the internal mental models that students construct (Mayer, 1997). Mental models are internal representations of what is described by a stimulus. They are triggered by words and visuals which have previous connections. A mental image created in response to words and their meanings, for example, guides further choice of words as students make further connections during learning (Craik, 1943). Mental models relate to the schemas described in Section 2.2 and these terms are sometimes used interchangeably. Others describe mental models as going beyond schemas by describing a combination of elements which is frequently too large to be held in working memory (D'Andrade, 2003).

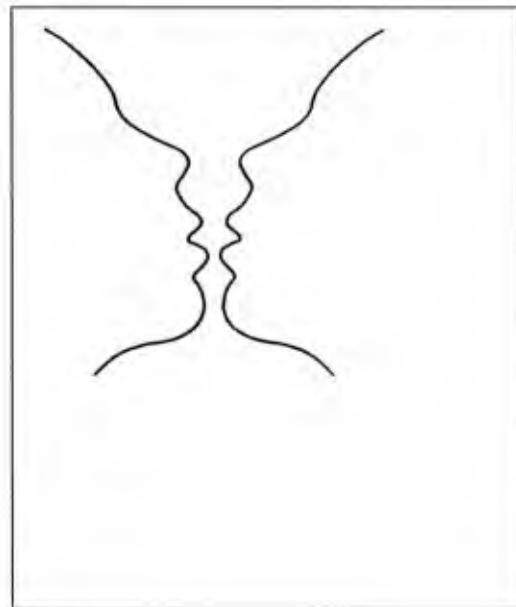
⁷ Gestalt theory is a theory of mind which acknowledges the ability of the brain to perceive whole forms and meaning from simple lines and shapes (Hothersall, 2004).

Words embody concepts, and using scientific words helps students to develop the associated concepts (Vygotsky, 1962). In science education, language is for recreating ideas which form the body of scientific knowledge, and which have already been refined by professional scientists (Sutton, 1992). Students of science need to be guided into a particular way of thinking about these phenomena.

Figure 2.1 Gestalt figure

Use of scientific terms must be scaffolded even if this adds cognitive load to the task of learning science. Learning technical language is both an essential part of science education and a major barrier to learning science (Wellington and Osborne, 2001).

Ausubel's (1968) studies showed how organisier ideas can be explicitly introduced to guide the way people think about new phenomena. The role of organising ideas is exemplified by the famous vases/face figure developed by the Danish psychologist Edgar Rubin (2009) (Figure 2.1). If the idea of a vase is suggested, the viewer will see vases rather than faces in the Gestalt figure. In the same way, ideas from prior learning frame what students see in new scientific information (Sutton, 1992).



The role of organising ideas was discussed in the context of the basic ideas of a domain which frame how learners prioritise their attention in Section 2.5.2. This idea suggests that the mental model which students construct of *Acetabularia* depends on the connections with their prior learning that are triggered by the visuals and text in the tutorial. In turn, students' interpretation of what is happening in the Hammerling experiments relies on this mental model to link with prior learning of nested ideas that explain the control of development.

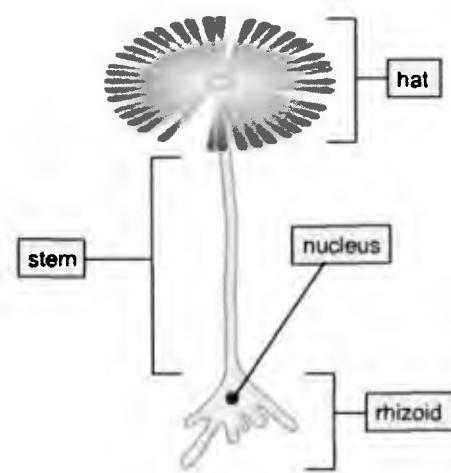
Quintana *et al.* (2004) argue that the formalisms used by scientists do not necessarily represent the way learners think intuitively about phenomena. Experts can use formalisms to detect meaningful patterns in problem-solving situations, but this task may be overwhelming for learners. Scaffolding strategies provided by Quintana *et al.* (*ibid*) under their Guideline 1 suggest using visuals and language which bridge with learners' intuitive ideas. This study suggests that scaffolding also needs to acknowledge the need for explicit

organising ideas which mould learners' interpretation of the media used to present ideas, in this case the visuals of *Acetabularia*.

Interpreting the visuals and descriptions of *Acetabularia* to construct a mental model of the organism is a pre-requisite for learning in the context of the tutorial. The data from this study suggests that the visuals of *Acetabularia* in the SNAB tutorial excite models of multicellular plants rather than models of single cells (see data in Section 4.2.2). Without an understanding of the scale and detailed structure of the organism, the visual of *Acetabularia* (Figure 2.2) could be 'seen' as a plant. 'Plant' then becomes the organising idea, and students may fail to draw on ideas from cell biology which could be used to interpret the data from the Hammerling experiments.

To bridge learners' intuitive understanding as suggested by Quintana *et al.* (*ibid*), designers must be aware of the prior connections that words and visuals excite. As the tools for reasoning, mental models are a product of science education which should be explicitly acknowledged. Constructing the mental models and new connections that they elicit (Kahneman and Tversky, 1982) is a role of scaffolding in inquiry learning.

Figure 2.2 Visual of *Acetabularia* used in the tutorial



Parallel, conflicting mental models

The idea that students appear to use alternative models for *Acetabularia*, even though these are inconsistent with each other, has been reported in different science education contexts. Leach and Scott (2002) inferred that many lower secondary school students recognise the logical implications of specific pieces of evidence in relation to different models of simple series electrical circuits, but resolve logical inconsistencies by selecting different models to explain the behaviour of different circuits. They do not draw upon the epistemological principle of consistency that is an important feature of science. Their everyday social language does not appear to recognise that scientific models and theories ideally explain as broad a range of phenomena as possible.

Linn, Davis and Bell (2004) explain that the ideas which form a student's repertoire may be fragile and fragmented. They may be bound to particular contexts, and may even conflict with each other. Students may seek to make ideas coherent by limiting their context rather

than developing the big ideas that are applicable across contexts. For example, students may decide that insulators work for hot but not cold materials (Leach and Scott, 2002).

When students refer alternately to *Acetabularia* as a 'plant', 'cell' and 'alga', they are demonstrating that their mental model of *Acetabularia* is not robust. Assuming that what they call *Acetabularia* is an indication of the mental model they are using, it appears that, as in the example of insulators above, students will draw on parallel, conflicting models as needed.

According to Linn and Hsi (2000), and Leach and Scott (2002), students are more likely to be able to apply mental models for background science ideas to broader situations if these models are robust. If concepts of *Acetabularia*, or the entities which contribute to explanations of development from prior learning, are fragile, SNAB students will only be able to apply these ideas in the contexts in which they have been learnt. The literature on misconceptions, discussed in the next section, suggests that a pedagogical underpinning for design can't assume that prior learning will always represent the desired scientific interpretation of phenomena.

The problem of misconceptions

The importance of prior learning is explained by constructivist theories which describe how the way that new material is processed depends on existing schemas (Anderson, 1983). One of the major challenges in learning science is that prior learning may have a negative effect in some situations. If new knowledge does not fit into existing frameworks that students hold, schema construction may be inhibited.

The frameworks that students use to understand science often differ from the accepted scientific explanations. These frameworks have been described as alternative conceptions (Arnaudin and Mintzes, 1985), naïve conceptions (Berthelsen, 1999), preconceptions (Gallegos, Jerezano and Flores, 1994) alternative frameworks (Driver, 1981), erroneous ideas (Sanders, 1993), children's science (Gilbert, Osborne and Fensham, 1982) and misconceptions (Fisher, 1985).

Relevant prior knowledge that students could draw upon to explain the events in the *Acetabularia* tutorial includes ideas about cell biology, genes, protein synthesis and development. Protein synthesis and the role of genes are introduced in the previous topic, SNAB Topic 2, in the context of a faulty gene in cystic fibrosis. Students need to apply this knowledge in the context of development in *Acetabularia*. The misconceptions literature

suggests that students may hold a range of ideas about genes and genetics which present a barrier to learning about development in *Acetabularia*.

Genetics is acknowledged as a difficult topic within biology education, and there is evidence that students do not fully grasp the mechanisms of inheritance or gene action. Students come to advanced level (post-16) biology with information about genetics from their pre-16 science courses, but they also have their own observations and social experience which inform their ideas. Studies have shown that students' views on the action of genes are not necessarily consistent with scientific theories. Use of the terms 'genes', 'DNA' and 'chromosomes' are often interchanged in their explanations (Lewis and Kattmann, 2004). This finding is reflected in the data from this study which shows confusion around the relationship between whole organisms, cells, chromosomes and genes (see Section 5.3.2).

A big picture of the connection between mechanisms on the micro and macro level is important. Students struggle to make links between genetics at the macro (individuals which have genetic traits), micro (DNA and chromosomes) and symbolic (genetic diagrams) levels (Mbajiorgu, Ezechi and Idoko, 2006). Barriers to learning may also be due to lack of understanding of the physical science principles that underpin the biology as discussed in Section 2.5.2. in the context of the big stories of science. This can prevent students relating to different levels of organisation where students are uncertain of the hierarchy of atoms, molecules and cells (Berthelsen, 1999).

In the *Acetabularia* tutorial, micro-level mechanisms such as the production of chemical signals by the nucleus are needed to explain macro level observable results in the development of specialised parts of the cell. Students need to relate what is happening in the Hammerling experiments to events within a single cell if they are to understand causal mechanisms for their observations.

Quintana *et al.* (2004) point to the potential barrier to learning presented by scientific formalisms and terms. There is evidence that students become particularly lost in the science jargon used in genetics (Lewis and Kattmann, 2004). The terms used in the *Acetabularia* tutorial also include words used in everyday life, such as 'hat' for the top part of the cell, and 'stem' for the long extension between an *Acetabularia*'s hat and rhizoid. This use of everyday terms has been found to confound students' scientific ideas, if they fail to distinguish between old and new meanings (Gilbert, Osborne and Fensham, 1982). There is evidence from this study that the scientific terms and everyday terms used with new meanings in the tutorial may present a barrier to learning (see Section 5.3.2).

The next section continues the discussion of the importance of students' previous knowledge and understanding in the context of the challenge of resituating prior learning.

2.6 Supporting students as they resituate prior learning

The task decomposition of the *Acetabularia* tutorial set out in Chapter 3 lists the science ideas and inquiry processes which were identified through the analysis in this study (Section 3.2). The content of the tutorial was divided into background science ideas which are the generic science topics such as genetics, cell biology and protein synthesis, and contextual science ideas, which are specific to the context of learning through the Hammerling experiments. The inquiry processes are based on those listed in the American Association for the Advancement of Science curriculum concept maps (AAAS, 2001), and also reflect the areas listed by Quintana *et al.* (2004) in their description of inquiry summarised from the literature.

The inquiry processes and background science ideas could potentially be resituated into different contexts. The background science ideas listed in the task decomposition have all been visited in previous topics, so the *Acetabularia* tutorial should involve resituating these rather than learning them for the first time.

2.6.1 Situated cognition

Lave (1988) describes how subject knowledge and skills are taught and used to solve specific problems within a particular context. If the knowledge and application are too closely tied to the situation, it is often the case that the same skills can't be applied in other structurally similar situations. The interaction of the subject content with its context is therefore of crucial importance. The development of skills and knowledge in a variety of contexts is needed to develop the ability to resituate this learning. The idea of situated cognition describes learning in authentic contexts, which would normally draw upon the knowledge being learnt to solve problems (Lave and Wenger, 1991).

Resnick (1987) describes the separation between 'knowing' and 'doing' in traditional learning. Traditional learning approaches emphasise teaching of abstract and de-contextualised, but widely usable, theoretical principles, concepts and facts. This resonates with Ogborn *et al.*'s (1996) idea of concepts as entities which are abstracted from their context, and which can be resituated to solve future problems in new contexts. The

problem with learning of decontextualised information, stored as facts rather than as tools, is that this knowledge may remain 'inert', and will not be more widely applicable (Collins, Brown and Newman, 1989).

Bransford *et al.* (1990) discuss how, even when students already know relevant strategies, they do not appreciate when to use these strategies when solving traditional word problems. In one study, Bransford *et al.* (*ibid*) used video-based learning anchors as guides to shape pupils' understanding of the contexts for inquiry. They found that students became immersed in the problem as a result of the vivid, affectual details present in video compared to verbal descriptions of the same problem. As a result of this deeper appreciation of the problem, students were able to come up with problem-solving strategies.

These studies suggest that, when the interdependence of situation and cognition are ignored, learning is not retrievable to solve future problems. Knowledge becomes the final product of education rather than a tool to be used and applied dynamically (Herrington and Oliver, 2000). Scaffolding strategies which explicitly support resituating of knowledge and skills may increase the effectiveness of inquiry approaches which draw on prior knowledge.

2.6.2 Scaffolding to support resituating of learning

Marton's (2000) theory of variation posits that, if the learner can experience variations of a phenomenon, this is an effective way of perceiving the phenomenon. During learning, repeated instances of a concept are necessary to expose learners to variations. This allows learners to abstract the concept. The theory of variation is based on the premise that learning involves discerning a phenomenon from its background. If there is no variation, then there is no discernment, because people do not pay attention to situations or things that are always the same. Marton's theory builds on Jonassen's (1991) idea of the need to present multiple perspectives on and approaches to a problem, stressing the interrelatedness of ideas. Jonassen's perspective comes from social constructivist theory, which suggests that students process new knowledge more effectively when multiple perspectives on a problem are openly expressed and considered during learning (Jonassen, 1991).

In a study of use of software showing a simulation of an electrical circuit, Hennessy *et al.* (2007) describe how one teacher made a learning activity of evaluating similar models on the internet. He also asked students to contrast their own ideas with explanations (of the photoelectric effect) from the internet, textbook and himself (the teacher). This act of

explicitly analysing the variation between different models representing the same phenomenon proved to be a powerful learning activity.

Schoenfeld's (1987) work on resituating learning to solve mathematics problems argues for development of understanding of the social situations which encourage fluency in making the appropriate connections. He describes how reflecting on learning can promote metacognition of what a problem is about and how it was solved. This practice builds a sense of a community of learners working through problems, and promotes the possibility of students making connections between mathematical concepts in different contexts. Schoenfeld (*ibid*) suggests that once the right contexts and environments are achieved, the difficulties students have with making connections between mathematical concepts in different contexts will no longer be a problem.

Quintana *et al.*'s (2004) scaffolding strategies draw on constructivist theories which acknowledge the role of prior learning. Quintana *et al.*'s (*ibid*) scaffolding guidance acknowledges that visuals and text which bridge with prior learning are not sufficient to bring about conceptual change alone. The scaffolding strategies show how prompts can encourage students to articulate their arguments, synthesise explanations and monitor and evaluate their learning. The strategies which Quintana *et al.*'s (*ibid*) scaffolding guidelines promote resonate with Marton (2000) and Schoenfeld's (1987) call for learning activity to involve this type of metacognition of learning processes. These pedagogic strategies apply across conceptual content and the inquiry skills and processes drawn upon in problem solving.

Resituating knowledge relies on scaffolding that bridges between the context where learning originally took place and the new context. Marton (2000) and Schoenfeld's (1987) work suggests that this should be an active process, where understanding of and discussion about phenomena across different contexts contributes to the richness of students' model of the phenomena. This work also implies that experiencing phenomena across a range of contexts supports conceptual change.

Appleton (1997) describes conceptual change during science lessons in relation to Piaget's (1950) terms of assimilation and accommodation. Appleton explains what happens when learners are confronted with new information. He suggests that new knowledge is compared with relevant existing knowledge. New and existing knowledge may produce an identical fit, needing no change to existing knowledge to form an explanation of the new phenomena. Alternatively, there may be an approximate or incomplete fit, with different

degrees of cognitive conflict. Appleton's ideas reinforce the idea put forward in Marton's (2000) theory of variation, as comparing new and previous knowledge involves discerning differences in the manifestations of a particular phenomenon.

Whereas Marton (*ibid*) describes gradual shifts in understanding as students experience variations in phenomena, Appleton describes conceptual change by emphasising the conflict between old and new knowledge. When there is sufficient conflict, Appleton suggests that students will seek to reduce it by amending their ideas and beliefs (Appleton, 1997). Changing students' schemas for a particular scientific idea may be difficult if the existing schemas have worked well in the past for solving problems which the learner comes across. This idea also suggests an explanation for why students often employ parallel, conflicting models, as discussed earlier. Only when students are convinced of the function of the new knowledge in problem solving is the new at all likely to replace the old (Giordan, 1996). Appleton's (1997) view of cognitive change as a result of conflict can be seen as one of many ways to experience the variation described by Marton (2000), so these ideas are not mutually exclusive.

Teachers adapt the support provided to individual learners by monitoring learning that is taking place. For example, an experienced teacher would detect confusion in the models which students draw upon to explain a phenomenon and support students as they work through cognitive conflict. Teachers scaffold to different extents through processes such as explaining unfamiliar language as it is used, and drawing attention to unintuitive features of complex diagrams. Software is normally designed for use by a range of students, and the scaffolding tools available for the varying needs of students are limited compared with the repertoire of a human teacher. Software can rarely provide the diagnosis and adaptive quality that effective fading of scaffolding demands (Puntambekar and Hübscher, 2005). On the other hand, the affordances offered by well designed software can compensate to an extent for the difficulty of providing fine-tuned, personalised scaffolding in the large class situations found in most schools (Rogoff, 1990).

The support needed for learning through science inquiry reflects the complex nature of the tasks involved. Quintana *et al.* (2004) chose this domain for their scaffolding design framework, as an example of 'ambitious learning' which is 'cognitively complex' (p. 341). The following section discusses the challenge of complex learning using theories of cognitive load.

2.7 Cognitive load

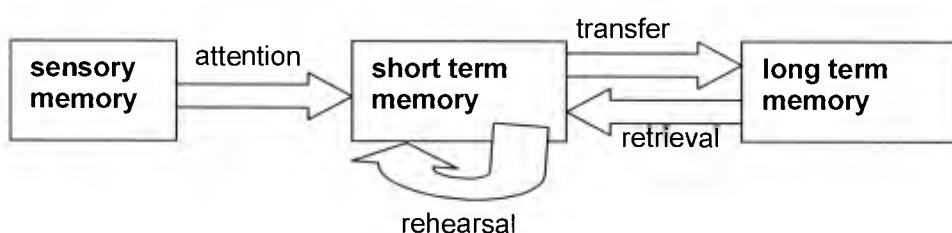
2.7.1 Cognitive load imposed by complex learning

Scaffolding demonstrates an awareness of the need to break down learning into manageable chunks. Cognitive load is a useful theory which helps to explain how scaffolding works. The need for scaffolding of science inquiry, which is the context for this study, reflects the highly complex nature of learning in this domain, as discussed so far in this chapter. Knowledge of the architecture of working memory from cognitive sciences has led to changes in the view of scaffolding for inquiry learning. The development of a theory of mind with a working memory that processes incoming stimuli mirrored the cognitive revolution in learning theories. The model of working memory acknowledges conscious processing before information is stored in long term memory.

Working memory is known to be limited in size, both in terms of capacity and duration. Overload of working memory during complex learning tasks will inhibit the formation of cognitive frameworks in long term memory, known as schemas. This section describes the implications of cognitive load theory for learning resources, and, in particular for the design of scaffolding.

Sweller and Chandler's (1994) work on cognitive load during learning uses the idea of limited short term or 'working' memory, based on Atkinson and Shiffrin's (1968) model of the mind (Figure 2.3). This multi-store model describes a sensory memory which briefly stores and transfers information from the sense organs to the short term memory. Information can only be stored in the short term memory for around 30 seconds unless it is actively rehearsed, and can only hold seven (+/- 2) 'chunks' of information at any one time (Miller, 1956). Information that is processed through conscious attention passes into long term memory, where it can be stored indefinitely.

Figure 2.3 Atkinson and Shiffrin's multi-store model of memory (2003)



Working memory holds the information that we are aware of. Inputs from the sensory channels (vision, sound, tactile, smell etc.) or from long-term memory (previously learned material) are held in the working memory while the information is being processed (Atkinson and Shiffrin, 1968). Both processing and holding the material being processed take up the limited capacity of the working memory. If material to be learned is too complex, there is too much of it presented at one time, or there are too many overlapping demands on the working memory due to the nature of the task being carried out, then learning will be inhibited (Sweller and Chandler, 1994).

Cognitive load is affected by properties of content being learned and the way that the material is presented. Intrinsic cognitive load is applied by complex topics where the sub-topics comprising an overarching topic do not form individual entities which can be understood. Intrinsic cognitive load is also imposed by the terminology and symbols used to communicate science, as these are additional elements to be understood and integrated with other information. Extraneous cognitive load is independent of the topic, and can be imposed by the presentation of learning materials. Integrating material split between text and visuals increases cognitive load, for example (Sweller, 1988).

Effective learning strategies maximise the strengths of long term memory through schema creation, and reduce the load on working memory through automation of processing. Schemas allow learners to apply problem solving strategies automatically to a range of new contexts without having to 'pay attention' to the process through conscious control (Sweller and Chandler, 1994).

Ideally, learning resources maximise germane cognitive load, generated by mental activities that are directly relevant to the construction of schemas, and minimise extraneous cognitive load imposed by the medium. Studies provide evidence that pupils with low working memory capacity frequently made errors in complex tasks, and failed to complete them. They struggle to follow complex instructions, and tended to lose their place in the task (Sweller and Chandler, 1994). It is important that features of educational resources that add to cognitive load are identified, and features which support learners with low working memory are emphasised (Gathercole and Alloway, 2008).

2.7.2 Conceptual problems with cognitive load theory

Cognitive load theory, based on the idea of limited working memory, works within this thesis, providing an explanation of the need for scaffolding during complex learning. The idea leads to designs which aim to optimise working memory capacity, and to minimise

cognitive load. The theory has, though, been questioned from conceptual, methodological and application-related perspectives.

de Jong (2010) argues that the different types of cognitive load are not ontologically equivalent. For example, intrinsic load is described by Sweller and Chandler (1991) as a function of the material, where germane load refers to the processing that takes place during learning. de Jong asks how cognitive load can exist, as suggested by the concept of intrinsic load, without action on the part of the learner. This argument produces a second conceptual problem with the idea of additivity. Sweller and Chandler's (1991) description of cognitive load assumes that intrinsic, extraneous, and germane cognitive load all add up. If learning is to occur, these must not exceed the capacity of our working memory. If, as de Jong suggests above, the different types of cognitive load are not ontologically equivalent, then it is difficult to see how they can combine with this implied additive effect.

The distinction between germane and extrinsic load is also problematic. The distinction between these types of load is highly dependent on learner characteristics and learning objectives (Moreno *et al.*, 2009). For example, it is not clear if extrinsic load is entirely something which exists as a property of poorly designed materials, or whether 'mistakes' or unnecessary processes on the part of the learner can contribute (Schnotz, W. and Kürschner, 2007).

More recent challenges to the cognitive load theory draw on evolutionary interpretations. For example, Geary's (2008) evolutionary account distinguishes between biologically primary information which is essential for survival and secondary information which is culturally important, but which we have not evolved to acquire. For example, learning associated with face recognition and speech occurs rapidly and with little effort. On the other hand, information of secondary biological importance such as mathematics and reading require explicit instruction, conscious effort by the learner, and extrinsic motivation for learning. It is likely that primary information includes generic problem-solving strategies, and that these are acquired at a young age due to the survival advantage which they confer. While there may be a continuum between primary and secondary biological knowledge, making the categorisation of content to be learnt difficult, this evolutionary theory suggests it is worth considering an approach to learning that focuses on organising automatically-acquired primary skills to facilitate learning of secondary content (Paas and Sweller, 2012). Evolutionary approaches to explanations of learning based on cognitive architecture certainly add nuance to the earlier cognitive load theories. They provide a rationale for

predicting potential cognitive load during learning, and suggest strategies for using automated learning process to the advantage of learners.

Methodological problems with cognitive load theory include the fact that there is no way to measure it directly. Three types of techniques are used in studies which aim to measure cognitive load: self-ratings through questionnaires; physiological measures such as heart rate and fMRI scans; and secondary tasks such as tests and application of knowledge (Paas et al. 2003). Mayer et al. (2008), for example, suggest that germane processing can be implied through results of a test of problem-solving transfer. Earlier, Mayer et al. (2002) admit that their argument for cognitive load would be 'more compelling' (p.180) if there were a direct measure of cognitive load, rather than having to induce this from tests.

de Jong (2010) raises the additional methodological problem that most studies aiming to measure cognitive load are conducted in labs. The application of this to real life situations is in doubt, as lab experiment participants may have no specific interest in learning the material which is the subject of the experiment, and are often given a very short study time (de Jong, 2009). When tested in classrooms or other more real life situations, a number of findings have not held up, or have even been reversed.

Although the validity of cognitive load is being critiqued from various perspectives, it remains useful as a model for linking cognitive architecture and design of learning materials. The focus of this study is scaffolding design, and the idea of scaffolding is based on the assumption that learning can be represented by a 'load' which can be alleviated with appropriate support. Theories of cognitive load work to explain scaffolding. While cognitive sciences wait for a more useful explanation of phenomena currently explained by this theory, it serves as the best available model in this and many other studies.

2.8 Conclusions from the review of the literature

This review of the literature sets out the theories of learning relevant to science inquiry learning. The implications for scaffolding learning in this domain emerge from a view of learning as a socially constructed activity, situated in authentic contexts. Learning science is complex, and requires coordination of concepts, many of which are difficult and abstract, with processes of the discipline. The concepts which need to be applied to explain data in an inquiry have frequently been learnt in a different context, so have to be resituated. Science inquiry processes also have to be applied across a range of contexts.

The mental models of natural phenomena which students hold should evolve during learning, and scaffolding must aim to avoid building flawed models which will present barriers to future problem-solving in new contexts. Learning tools should explicitly support building of big ideas in science, which connect individual elements of learning, and produce overarching principles which serve to explain phenomena broadly, across a wide range of contexts.

The cognitive load imposed by such complex learning may present a barrier to learning, and the needs of learners as they carry out inquiry learning should form the basis of scaffolding design. Although the validity of the concept of cognitive load and the methods used to measure it have been queried, it offers a useful model for design of educational materials.

Pedagogical support for learners, tailored through empirical research, is needed to communicate the processes of the discipline, coach through hints and embedded guidance, structure complex tasks and encourage articulation and reflection of learning (Collins, Brown and Holum, 1991; Bell and Davis, 2000; Yelland and Masters, 2007). These elements need to be synthesised and integrated to achieve the result of effective learning resources.

The questions raised by the accounts of the relevant literature in this study include whether or not generalised theories from educational research and generalised design principles from educational design research can be synthesised and presented in a way that is useful to designers across a range of design contexts.

The next chapter sets out the methods used in this study, which tests the Quintana *et al.* (2004) scaffolding design framework through the case of the SNAB *Acetabularia* tutorial. The study uses empirical data from students carrying out the tutorial and a task model of the tutorial, to explore the scope and comprehensiveness of the framework, and to explore how design principles can incorporate relevant pedagogies.

Chapter 3 Developing a methodology for principled software design

3.1 Introduction to the methodology

This study aims to identify and develop principles for software scaffolding design in the domain of science inquiry. The previous chapter reviewed a range of literature from science educational research and research on inquiry learning that underpins pedagogic approaches to scaffolding science inquiry. One problem facing software developers is that this collected knowledge base from the literature is not necessarily presented in a way that is useful for design.

Educational design has not traditionally articulated shared approaches for the purpose of building on past work. This is partly because, until recently, there has not been a strong community with the purpose of building the knowledge of the discipline in the way that educational research proceeds through publications and conferences. For this reason, it is important that this study builds on a previous attempt to distil the knowledge of the discipline rather than starting afresh. By critiquing the Quintana *et al.* (2004) scaffolding design framework, this study explores an existing approach to principled design which brings together the literature and practice of the domains relevant to science inquiry learning.

This chapter describes the educational design experiment carried out in the context of a scientific electronic tutorial developed for the Salters-Nuffield Advanced Biology (SNAB) course.

3.1.1 My position as researcher

Using research-based principles to analyse learning experiences, the main purpose of this study is to provide insights that could inform future software developments, and contribute to accumulating the craft knowledge of educational design. Central to this study is the aim of gaining insights into the situations and contexts where the support of ICT tutorials is most effective, and into scaffolding learning through science inquiry more generally.

As the designer of the SNAB electronic resources, I am aware that I have a unique position, and understand that my personal interpretation of the data will be affected by my position as developer of the tutorials. I argue that my motivation is to understand better how electronic tutorials might scaffold learning and how general design principles can be distilled from a particular case: I do not consider this study simply as an evaluation of electronic tutorials using classic inquiries.

3.1.2 Learning from pilot studies

This study follows a pilot which informed decisions about the final research question and methodological approaches. The initial research question for the pilot was 'How do ICT tutorials affect students' ways of experiencing phenomena and developing understanding in advanced level biology?' The study used a positivist approach leading to an experimental design. This assumed that there would be a measurable added-value effect from students using a SNAB ICT tutorial based on Hammerling's classic experiments on *Acetabularia*, when compared with students learning the same content through a different medium, in this case a paper activity. The question 'how?' also implied an experiential approach, where phenomena are described as they interact with students, so qualitative data was also considered important, if secondary to the main, quantitative data.

The experimental groups of advanced level biology students involved a treatment group who carried out the ICT tutorial, and a control group who carried out the same activity as a paper-based version. The average GCSE scores of the students in both treatment groups were used to control for prior learning and ability in the analysis of the results.

The data for the pilot comprised recordings using screen capture software to provide a record of students' screen movements. The software also provided an audio recording of students' discussions. Audio recordings only were made of a group of students carrying out the paper-based activity. These two sets of recordings, from a single AS level class in Centre A, followed pre-tutorial tests. The responses to multiple choice questions within the activity were scored against a mark-scheme, and students from both treatment groups were given two additional paper-based activities (Questions 6 and 8). The purpose of Question 6 was to test students' understanding of the classic experiments shown in the tutorial. Students were asked to design their own experiment based on their understanding from Hammerling's first three experiments. Question 8 required students to draw conclusions from each experiment, then link these conclusions to supporting evidence. A group of students were also interviewed after the lesson. A larger set (37) of pre- and post-

test data was collected in Centre B, with no recordings. The pre-test was the same as in Centre A, and the post-test was the same as Question 8 from Centre A.

The results of the pilot were much more nuanced than expected. For example, there was no statistically significant difference between the value-added scores of the paper-based treatment group compared with the scores of those carrying out an electronic tutorial when the entire activity was considered. There were, though, individual questions which showed a statistically significant difference between treatment groups, some showing a value-added effect for the ICT tutorial and some for the paper-based activity. The value added scores for Question 6 and 8 showed that students in the ICT treatment group were more consistently successful at using their knowledge and understanding to plan a new experiment, and they learned how to construct conclusions backed by evidence more effectively.

It became clear that it was neither possible nor necessarily of interest to be able to make claims about the superiority of one mode for the entire activity over the other. Claims at the level of the whole activity provided little information which could inform future design, and this was a key motivation for this study. The quantitative analysis did, though, highlight how students' performance was dependent on features of the tutorial at a level of granularity corresponding to individual sections or even individual screens.

Analysis of the transcripts of recordings and interviews revealed phenomena which provided information about how the students interacted with the ICT tutorial and with each other as they worked. A study of students' utterances, linked with their mouse movements, identified a range of observations which could contribute to explaining the results of the quantitative analysis. For example, the screen capture recordings and transcripts together provided evidence that students carried out 'test clicking' to check the answers to the multiple choice questions, rather than discuss the questions until they agreed an answer. Utterances such as "Doh. Maybe it's er that one", along with the recorded mouse movements, showed that students guessed answers to multiple choice questions both before their initial submissions and after feedback telling them their initial response was incorrect.

The data also revealed a range of other interesting phenomena which could have been investigated further. These included the observation that students carrying out the paper activity appear to talk more than those carrying out the ICT tutorial and the incidence of evidence for affective phenomena. Comments indicating affective reactions to the tutorial

(delight, boredom or frustration) were coded as 'positive' or 'negative'. Positive comments such as 'I love this bit ooooooh' and negative comments such as 'No we're rubbish' were linked to events in the tutorial. The ICT tutorial elicited a higher total number of affective comments, and a much higher proportion of positive comments. This phenomenon was potentially of interest according to the research on the connection between emotion and learning in relation to motivation, association of learning and recall, and the effects of emotions on cognitive processes (Anderson, 2000; Brandt, 2000; O'Regan, 2003).

The difference between students' inferior scores in the ICT tutorial activity and their superior ability to apply their learning about the Hammerling experiments compared with the control (paper-based activity) group was considered in the light of the qualitative data. The differences between the scores of the two treatment groups could be accounted for, for example, by the phenomena described above, where students' responses to the multiple choice questions in the ICT tutorial represent recordings of their first submitted answer. This could also account for the higher word count in the transcripts of the paper-based activity group. If there is an effect of using the ICT activity compared with the equivalent paper activity, the inconsistent results across the question scores in the tutorial suggested that analysis at the level of individual questions in relation to student performance would be necessary to explain this.

The approach taken in the final study uses a holistic analysis of transcripts, taking the position that this is the most useful approach for the purpose of educational design research. This approach, based on a constructivist epistemology uses qualitative analysis of the transcripts to consider the assumptions made about students' understanding by the tutorial design, and the nature of the learning outcomes. It focuses on the affordances for learning of individual tasks and tools which comprise the design of the tutorial. A more critical approach would explore assumptions present in the study in depth in relation to any claims made as part of the study, but this was not considered necessary in the context of design research, which aims for generalised principles.

The quantitative data suggested that it may be of interest to carry out similar experiments with larger sample sizes, but this assumes that a comparison between paper-based and electronic activities is a valid method to elicit knowledge about design principles. The assumption that learning outcomes and basic cognitive tasks were the same in the two types of activity (paper-based and ICT tutorial), were questioned by the pilot study data. If the scaffolding is not the same, then students may not be carrying out identical cognitive

processes, suggesting it is not possible to change the mode of the activity without changing a range of other significant factors.

For example, the ICT treatment group carried out manipulable (drag and drop) animations of the *Acetabularia* experiments while the paper activity group's information about the experiments was provided as a short sequence of still images. Previous studies have found that any advantage of animation over still images is highly dependent on the specific material (Höffler and Leutner, 2008) and that static images which require students to infer motion or a dynamic link between pictures apply cognitive load which may affect learning (Lewalter, 2003). Kalyuga (2008) found that the affordances of animated versus static images depended on the expertise of the learner.

As this study aims to inform future design, further analysis of quantitative differences between test and activity scores was not seen as particularly helpful in answering the questions raised by the pilot about how a specific tool in an ICT tutorial might change students' engagement with the content to be learnt. The range of phenomena observed in the transcript data showed that specific features present in the ICT tutorial (for example the multiple choice questions with feedback) elicited responses from students which could be explored further.

Designers need to know which individual tools within a software activity are helpful for learning, and what it is about their design that supports learning. The comparative study design of the pilot was rejected, and the recordings and transcriptions from the *Acetabularia* ICT tutorial became the focus of the final study, where they had been of more secondary importance in the pilot study. The design of the study shifted from a more positivist approach to a constructivist approach aiming to probe students' interactions with the tutorial through detailed qualitative analysis. This shift in position reflects Reeves' (2011) and Schoenfeld's (2009) positions about the need for small scale in depth studies for educational design research, discussed in Section 1.2.3.

The data from the paper-based treatment groups was not used in the final study, but the data from the 37 pre-tutorial tests and post-tests from Centre B allowed phenomena from the transcript analysis of Centre A recordings to be triangulated and validated through a larger sample-size using a semi-quantitative approach. This arrangement also avoided having to wait an academic year before the teaching groups were at the same stage in their course, as data was collected in normal lessons at the time when classes would have been carrying out the tutorials anyway.

Educational design research studies interventions through design experiments, leading to more effective designs and increased knowledge and articulation of the principles that underpin their impact (see Section 1.2). The argument for this approach addresses the criticisms of educational research having weak links with practice (Feast and Melles, 2010). It helps to answer questions about how and why particular interventions work, and leads to synthesis of knowledge about design. The final study takes the perspective of an educational design experiment by taking an existing resource and studying the interactions between tutorial and learners. What makes this study 'research' rather than another way of constructing knowledge about a social situation is the justification of a particular theoretical stance, and attention to the validity of the methodology and interpretive framework employed. As such, the final study needed a theoretical framework for the analysis and interpretation of the data.

Selecting the framework

Many frameworks exist for design or analysis of inquiry learning, design of scaffolding and software design (see Section 1.3). The final study could have focused on a number of different design elements or aspects of science inquiry learning. The focus on scaffolding led from the pilot study which suggested that software features may support student's learning in a way that changes the cognitive tasks by making these more tractable.

In the spirit of synthesising and articulating the knowledge of the discipline of educational design research (see discussion of this in Section 1.2), this study was designed to critique an existing framework rather than attempting to develop a new framework. The suitability of the Quintana *et al.* (2004) framework lies in its meta-analysis of existing frameworks for scaffolding reasoning and inquiry learning. The framework synthesises previous work in the specific domain of science inquiry learning. The synthesis and application of principles of specific relevance to the *Acetabularia* tutorial has already been carried out. The framework's guidelines are also based on pedagogic approaches to scaffolding, not software features. By addressing barriers to learning, it allows designers to consider a range of tools for addressing particular needs of learners. This approach allows the development of generic principles based on the interface between pedagogy and design. As such, the framework represents knowledge from the perspective of educational design research: it is principled, based on the literature on reasoning and science inquiry learning, while informing design.

In the final study, empirical data from students carrying out an electronic tutorial from the SNAB tutorial is used to test Quintana *et al.*'s (2004) scaffolding design framework. The

guidelines in the framework are critiqued in terms of their utility for characterising the existing scaffolding in the tutorial and for suggesting how the tutorial's scaffolding could be developed further. Together, the stages of this study contribute to a heuristic for principled software design.

The methods of the final study are presented in Section 3.1.3 as a study design, as the post-hoc redesign does not affect the validity of the data collection. The data from this study is presented in Chapter 4, and conclusions from the data are discussed in Chapter 5. Inferences, including suggestions for refinements to the framework and tutorial are presented in Chapter 6.

3.1.3 A summary of the methodology and methods

In a way that mirrors how Quintana *et al.* (2004) constructed their scaffolding design framework, this study develops a task model for the tutorial being studied, and identifies learning and barriers to learning. Quintana *et al.*'s (*ibid*) theory-driven approach to developing their framework involved three elements:

- developing a task model which encapsulates the scientific practices of inquiry from the literature
- providing a description of the obstacles which learners encounter
- producing scaffolding guidelines which show how tools can make the learning tasks more tractable.

In this study, the barriers to learning and instances where tools make the task more tractable are identified from empirical data. This contrasts with Quintana *et al.*'s (*ibid*) methodology which involved identifying learning and barriers to learning from the literature. This study then goes on to critique the framework by testing the guidelines against the data. The study comprises the following stages:

- Stage 1 Developing a task model with reference to concept maps for science inquiry and the relevant background science topics.
- Stage 2 Collecting and transcribing empirical data from students carrying out the *Acetabularia* tutorial.
- Stage 3 Analysis of the data to identify evidence of learning and barriers to learning with reference to the task model. As a result of the analysis of learning and the barriers to learning, the task model is refined and a focus for the study is identified.

- Stage 4 Testing the Quintana *et al.* (2004) framework using the data, through an analysis of the relevant evidence with reference to the guidelines in the scaffolding design framework. This stage is carried out in terms of the specific focus identified in stage 3.
- Stage 5 Development of recommendations for refinements to the Quintana *et al.* (*ibid*) framework and *Acetabularia* tutorial. These recommendations are the result of discrepancies between the data and guidelines.
- Stage 6 Reflection on the process for iterative design developed in the study.

3.2 Stage 1: Developing the task model for the tutorial

The tension between generalised and contextualised design principles was discussed in Chapter 1 (Section 1.2.1). The methodology in this study tests whether Quintana *et al.*'s (2004) framework of generalised guidelines can be reinterpreted in the specific context of the *Acetabularia* tutorial. For this purpose, a process which mirrors aspects of the development of Quintana *et al.* (*ibid*) framework was carried out.

The first stage of the process involved developing a task model for the tutorial. A task model in this context refers to the cognitive tasks that students engage in as they work through an educational resource. The model for the *Acetabularia* tutorial was developed iteratively, using the empirical data to refine the description of the tasks which students engage in as they carry out the tutorial.

A task model of the cognitive tasks framed the later analysis of learning and the barriers to learning identified from the data: it is only possible to describe how students' learning is being supported or is not supported sufficiently in the context of what it is they are trying to learn.

Testing the Quintana *et al.* (2004) framework in later stages of this study involved comparing the data with the scaffolding guidelines. This comparison relies on the assumption that the *Acetabularia* tutorial is attempting to scaffold the same inquiry processes as the strategies in the framework. Developing the task model of the *Acetabularia* tutorial using the categories in the Quintana *et al.* (*ibid*) framework without critiquing these would not necessarily test the framework's utility. The circular process of matching the framework's task model to the tutorial, then using the data from students using the tutorial to test whether the framework fits the task model of the tutorial would be self-referential. For this reason, task decomposition also referred to the benchmarks for the American

science curriculum produced by the American Association for the Advancement of Science (AAAS) (2001).

It would be surprising if the generalised task model from the Quintana *et al.* (2004) framework and the tutorial's task model did not show some correspondence, as both the framework model and AAAS (2001) benchmarks are derived from a wide literature base on learning through science inquiry. The benchmarks, for example, were produced from concept maps that have regard for developmental coherence, following the logical dependence of concepts on precursor ideas, and psychological coherence, taking account of students' pre-existing notions.

Evidence for the principled construction of the AAAS concept maps is based on references to the literature provided alongside the maps. For example, Rosebery *et al.* (1992) are cited as evidence of middle-school students' tendency to invoke personal experience as evidence in the section justifying the benchmarks in the maps for skills in evidence and reasoning in inquiry. Reference to Kuhn *et al.* (1988) provides evidence that 6th graders can judge whether evidence is related to a theory.

Reference to these progressive concept maps allows learning approaches to be related to individual aspects of science inquiry across a wide range of learning interventions. While it was important to highlight any areas where the specific example of the *Acetabularia* tutorial did not fit with the AAAS (2001) benchmarks, the benchmarks provided a reference point for the development of a task model for the tutorial.

Quintana *et al.*'s (2004) decomposition of learning through science inquiry leads to generalised design guidelines which can be applied in any science context. The framework's task model is justified in a rationale for each strategy which references empirical studies. For example, Strategy 1a: 'Provide visual conceptual organisers to give access to functionality' (p. 347) suggests that software should allow learners to interact with functionality to guide their deeper thinking about concepts. This strategy is underpinned by a barrier to learning identified from empirical studies, showing that students need support in making links with their prior knowledge. For example, novices may not see patterns in scientific situations that are apparent to experts (VanLehn, 1989), and there is often a gap between the way students think and the formalisms used to represent scientific phenomena (Sherin, 2001).

Early on in this study, significant deviations of the tutorial's task model from the model provided in the Quintana *et al.* (2004) framework were identified. These included the need

to decompose context and topic specific learning about *Acetabularia* and development in addition to inquiry processes. The decision to include science concepts in the task model for this study stems from evidence in the data. The data suggests that the process of developing explanations can't be separated from the context of the explanations. It shows how making sense of the inquiry relies on students accessing and resituating the appropriate background science. An analysis of the scaffolding needed to develop explanations must include an analysis of the science ideas involved in these explanations. The AAAS (2001) concept maps provided a decomposition of background science ideas which were relevant to the *Acetabularia* tutorial, in addition to science inquiry processes.

3.2.1 The task decomposition

A task model for the *Acetabularia* tutorial was produced by decomposing each screen and each task, noting the processes and science concepts needed to engage in the task. The task decomposition was carried out under three headings: *context-specific ideas* which pertain to *Acetabularia* specifically, more generic *background science ideas* and *scientific inquiry processes*. The task model was then refined iteratively through an inductive analysis of the empirical data of students learning through the tutorial.

Context-specific ideas

In the *Acetabularia* tutorial, the narrative of the Hammerling experiments dominates the design, and the way that new ideas are introduced. The learning outcomes of the tutorial include understanding of how development occurs in *Acetabularia* as evidenced in the Hammerling experiments.

The ideas that situate the background science concepts in the context of the experiments on *Acetabularia* are:

- 1) *Acetabularia* is a single cell with specialised parts (hat, stem and rhizoid).
- 2) *Acetabularia* is ideal for this type of inquiry, because it is large enough to dissect and manipulate.
- 3) A complete cell develops from any cell part that has the nucleus present, or from parts to which the rhizoid containing the nucleus has remained attached after removal of the hat.

- 4) A chemical signal travels between the nucleus and the cytoplasm, and these chemicals in the cytoplasm determine development of the cell parts.

The context of the Hammerling experiments introduces new background science ideas about cells as whole organisms with specialised parts. The tutorial uses the particular example of a single-celled alga, and shows how the cell can be dissected and rejoined and the nucleus transplanted to different parts to investigate the role of the nucleus in development.

Background science

The background science concepts that the *Acetabularia* tutorial aims to introduce overlap with the contextual ideas. They are more overarching or generalised than the contextual ideas, which are specific to development in *Acetabularia*. The analysis of prior learning of SNAB students in the next chapter (Section 4.1) shows that these background science ideas are not introduced for the first time in the *Acetabularia* tutorial. However, this is the first time that these ideas have been situated in the context of development in a single cell, single-celled organisms, or specifically, *Acetabularia*. The tutorial introduces the following background science ideas which, ideally, students should be able to resituate to a range of new situations:

- 1) Cells contain specialised structures.
- 2) The nucleus contains the cell's genetic material.
- 3) The genetic material contains the code which controls which proteins (and other chemicals) are made in the cytoplasm.
- 4) Chemicals in the cytoplasm control the cell's activities.
- 5) Development of characteristics (including specialised structures in the cell) is controlled by chemicals in the cytoplasm.

The numbering 1-5 does not imply a set order of progression for learning these ideas: understanding the role of the nucleus in cell development could potentially start with any one of these ideas and then proceed to the others.

Scientific inquiry processes

The *Acetabularia* tutorial also involves students in scientific inquiry processes. Intended learning outcomes from the tutorial include an enhanced ability to carry out these processes as part of a scientific inquiry. The main scientific inquiry processes were identified with reference to the curriculum progression maps for science produced by the American Association for the Advancement of Science (AAAS) (2001). The process tasks which students are involved in as they carry out the *Acetabularia* tutorial are:

- 1) Collecting observations.
- 2) Analyzing data (observations).
- 3) Constructing explanations.
- 4) Interpreting scientific representations and models.

3.2.2 Using the task decomposition to analyse individual screens

Once the overall task decomposition for the tutorial was established, this was used to identify the cognitive tasks which students engage in on individual screens of the tutorial. Table 3.1 shows the final task decomposition of a single screen, showing the first question after Experiment 2 in the tutorial. Each screen decomposition results in a different combination of background science, contextual and science inquiry process ideas.

Table 3.1 Decomposition of Question 3 in the *Acetabularia* tutorial

Question 3 (Question 1 after Experiment 2)				
Experiment 1	Experiment 2	Experiment 3	Experiment 4	
<p>Answer the following three questions about the experiment.</p> <p>Thinking back to Experiment 1, choose the correct response to the statement in the box.</p>				
<p>Question 1</p> <p>When the rhizoid is left attached to the stem, some sort of signal passes up the stem to the tip from the rhizoid, so the stem becomes able to develop a hat.</p> <p><input checked="" type="radio"/> This is a valid conclusion from both Experiment 1 and 2.</p> <p><input checked="" type="radio"/> This is a valid conclusion from Experiment 2, but the evidence from Experiment 1 suggests it is <i>incorrect</i>.</p> <p><input checked="" type="radio"/> This is a valid conclusion from Experiment 2 only.</p>				
<p>1/3</p>				
Contextual ideas				
<p><i>Acetabularia</i> is a single cell with specialised parts (hat, stem and rhizoid).</p> <p>A complete cell develops from any cell part that has the nucleus present, or from parts to which the rhizoid containing the nucleus has remained attached after removal of the hat.</p> <p>A chemical signal travels between the nucleus and the cytoplasm, and these chemicals in the cytoplasm determine development of the cell parts.</p>				
Background science ideas				
<p>Cells contain specialised structures.</p> <p>Chemicals in the cytoplasm control the cell's activities (which chemical reactions take place).</p> <p>Development of characteristics (including specialised structures in the cell) is controlled by chemicals in the cytoplasm.</p>				
Science inquiry processes				
<p>Collecting observations; Analyzing data (observations); Constructing explanations; Interpreting scientific representations.</p>				

3.3 Stage 2: Collecting the empirical data

The data collected in this study was from two mixed-sex sixth form colleges, referred to as Centre A and Centre B. The data consists of recordings of students carrying out the tutorial using screen capture software called *ScreenFlash*, recordings of interviews with students carried out after the tutorial, written answers to paper-based questions and written answers to pre-tutorial and post-tutorial tests.

3.3.1 Screen capture software as a tool for research

Software developers involve both users and experts to test new products. In this way, the industry can monitor audience needs and technical ability to inform further developments. In many ways the needs of software developers mirror those of educational design, where information about how people use software and the reactions it elicits are important. Commercial software developers use methods familiar to researchers. Formative and summative interviews, field studies, recording and analysing user testing and expert reviews, are all vital components to producing effective software.

In a paper on the various forms of analysis that can be used to study the way users interact with a computer applications, Hulshof (2004) discusses the most commonly used methods to track interaction: eye tracking, thinking aloud and log files. Eye tracking provides researchers with precise information about the type of information users are processing. The problem with this method is that where complex cognitive processes are being studied, interpretation of eye movements is not straightforward. Other studies use 'think-aloud' methods, which require users to provide a commentary on their processes, and which are more suitable for studying users working on complex tasks. Think aloud techniques require conditions and equipment that are not often available, particularly in a field study, and they may disturb the experimental subjects. Recording user actions in the computer's log files is popular in usability research, as it is easy to carry out, although the link between a recorded sequence of actions and its interpretation in terms of user reasoning may be more difficult than with other methods.

Usability testing of software is normally carried out in specially equipped labs, where users are asked to complete a series of tasks with the website or software. Data from comments, interviews, task success, ease of navigation and performance data are collected, summarised, and used as the basis for design recommendations (Invision, 2004). A usability engineer records the participants' actions and opinions, hoping to understand from this

their expectations and thought processes. Questionnaires are also used to record participants' opinions and preferences (Muller and Czerwinski, 1999).

Software tools are used to collect and analyse usability data. A scan recording of the screen and screen actions is made, alongside sound recording and video recordings of the participant's facial expressions and mouse movements. Other studies carry out 'contextual inquiries,' where participants are asked to carry out a task, such as 'send an e-mail', in their normal place of work or home. This is considered to be a very powerful way to understand user behaviour, because the data is collected in the context of the user's environment and the activity itself (Microsoft, 2009).

Various software solutions are available for "click-by-click" analysis of users' engagement with a software product in early stages of development. Rich recording technology (RRT) such as *Morae*, allows multiple data streams of video, system activity and audio to be recorded, automatically indexed, and later to be searched and analysed. This type of software allows statistical analysis of the users' behaviour in terms of routes through the software or website, time spent on a particular section, number of times a section or page is revisited and number of mouse clicks. Synchronisation of the data with information about what the subjects were doing allows points of interest to be contextualised (TechSmith, 2007).

Screencasting software takes a digital recording of screen activity. This type of software does not record system activity. Screencasting is mostly used to produce training and software demonstrations, but can also be used to record the action of software testers. Screencasting software includes *ScreenFlash* (UNFLASH, 2002), *Captivate*, *Hypercam* and *Camtasia*. These applications output Flash or AVI video files, have audio capture facilities and mouse-tracking. Screencasting and usability testing software provide video data to analyse for insights into users' expectations. Stumbling blocks in the software can be highlighted, along with areas of difficulty and features that are over-explained or under-explained. It is possible to add notes to the output, and mouse clicks are recorded on a timeline.

Screen capture software is widely used to produce web-based tutorials, and the effectiveness of these has been researched in many domains and at various levels from school to industry. For example, Folkestad and De Miranda (2001) studied the use of screen capture tutorials in instructing students in the use of computer aided design. Wales and Robertson (2008) carried out a study of the challenges faced by the Open University in

using screen capture to develop online literature search tutorials for their students. Brick and Holmes (2008) studied the effectiveness of using screen capture to make multi-modal feedback from tutors available to students at Coventry University.

The software can also be used as a tool for research, drawing on its affordances in usability testing, rather than being the subject of the research. Qualitative data collection often involves audio or video recording, and production of transcripts or notes made during observations. The use of usability software for research into student's learning through ICT tools is well documented, but there are few examples of studies which have used screen capture software specifically for the study of learning through software. Exceptions, where studies have used screen capture as a method of data collection, include Tort *et al.*'s (2009) study using *Camtasia Studio* software to record students' errors when using spreadsheets. The data analysis categorised on-screen moves, and was not concerned with audio recording of students' discussions. At Penn State University, researchers used screen capture technology to study students' interactions with the libraries' databases (Imler and Eichelberger, 2011). Again, this research used and analysis of screen movements alone, and is more similar to software usability research than educational research to explore learning.

Use of screen capture is also seen in a study to explore how different scaffolds facilitate students' learning in an online historical inquiry (Li and Lim, 2008). The study uses video of students working alongside screen capture, focus group interview, digital artefacts, and student survey to find how the students interact with scaffolds to achieve a better performance. In this study, carried out in a Singapore school, a combination of the video (visual and audio) recording and screen captures provided information about the online inquiry processes of students. The reason given for using both types of recording tool in this study is that screens showing student's online navigation behaviour is captured alongside verbal interaction and facial expressions.

A study which makes use of the full affordances of screen capture software to collect data on students' interactions with the software and their conversations as they learn is Zhang and Quintana's (2012) study of their online inquiry scaffolding tool *IdeaKeeper*. Their study used primary data sources of screen videos of students' online activities. Computer activities and verbal conversations were captured by *Camtasia* screen capture software. Further data was also collected and analysed in the form of paper notebooks of student's work during the inquiry, and separate observational notes were made on the students' off-line activities. This combination of data from different sources allows triangulation of inferences about the learning and the affordances of the scaffolding tools.

In this study it was useful to be able to link students' conversations with the tasks they were carrying out at the computer. It was also necessary to have a way of recording the submission of multiple choice answers as students carried out the electronic tutorials. Usability testing software provided a tool for the purpose of simultaneous recording of screen actions and audio.

ScreenFlash

ScreenFlash software was used to record students carrying out the SNAB ICT tutorials, because it provided sufficient data to link screen actions with what students were saying. Students' cognitive processes as they learn can't be measured directly, but a combination of these two forms of data allows useful inferences to be made. Additional functionality associated with rich recording technology such as *Morae* was not necessary for this particular study. The main problem with screencasting software is that it noticeably slows the running of some applications. In the SNAB software this is most noticeable in the animations, but was not judged sufficiently significant to affect students' engagement with the activity for the purposes of this study.

Figure 3.1 A ScreenFlash screen showing a recording of students carrying out the tutorial

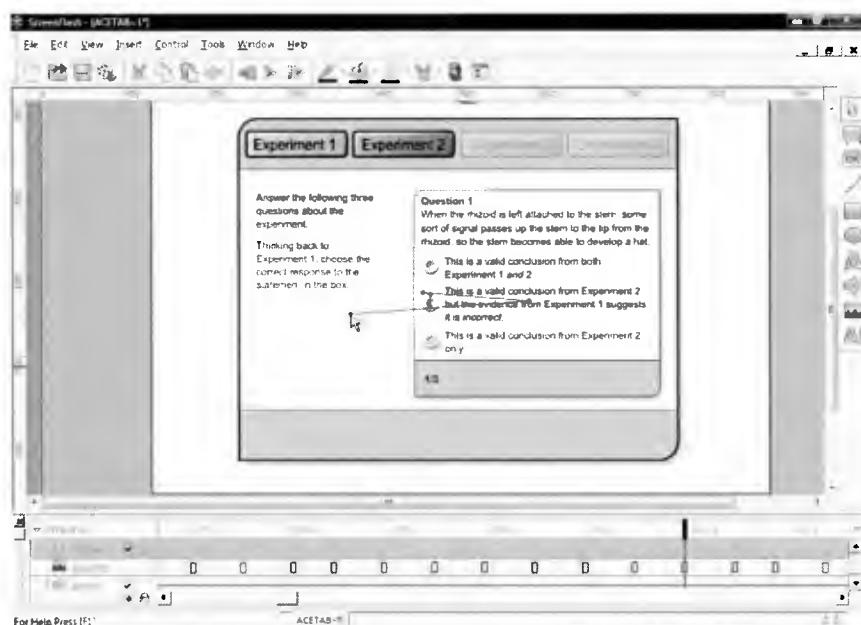


Figure 3.1 shows the interface of ScreenFlash software in a recording of the *Acetabularia* tutorial. Below the recording of the computer screen, the sound and mouse click recordings are visible. The tracks on the screen show the trail of mouse movements and clicks.

The software was particularly useful for providing a context to help interpret ambiguous utterances (for example it is possible to see what students are discussing even when they refer to 'it') and for recording the submitted answers to the multiple choice questions.

The software also showed evidence of test clicking to find the answer to multiple choice questions, through mouse movements. The use of *ScreenFlash*, combined with data from students' written activities and tests reflects the approach of Zhang and Quintana (2012) described above. In a similar way, this study analyses video and audio data from the screen capture software, and triangulates this with written student work and interviews.

3.3.2 Data from Centre A

The first set of data was collected from an AS class of 17 students in Centre A. 10 of these carried out the tutorial electronically. The data, relating to students carrying out the *Acetabularia* tutorial, was collected during a normal lesson, within the planned lesson sequence for the department.

Eight students in the class were recorded as they carried out the tutorial. Four students were selected randomly from numbers in the register, and these students chose their preferred working partner to form four working pairs. Screen movements and the students' discussion were recorded using *ScreenFlash* software (UNFLASH, 2002) as students carried out the tutorial. Collecting data using *ScreenFlash* was described in Section 3.3.1.

The students being recorded using *ScreenFlash*, along with others in their group, were given a test to carry out before the tutorial. The pre-tutorial questions aimed to test specific knowledge and understanding about genes and the role of the nucleus in development. Students were asked 'What is a gene?' and where they might find genes in a cell. Questions 3 and 4 ask how genes affect processes in a cell, and how a gene might influence development of a remote part of a cell (see Appendix 1).

The students were also given two paper-based activities to carry out, which probed the application of knowledge from the tutorial. The first paper-based question was given out after students had completed the third experiment in the tutorial. For reference, this question is numbered in sequence with the questions in the tutorial, as Question 6. Question 6 involves planning an experiment using two species of *Acetabularia* to investigate the role of the nucleus in development (see Appendix 3).

The second paper-based activity, Question 8 (see Appendix 4), provided at the end of the tutorial, gets students to complete a table with their own conclusions from the experiments, along with evidence which they select to support or refute the conclusions.

Eight students were then interviewed after the lesson, and the interviews were audi-recorded. Interviews depended on the availability of students following the lesson and at lunch time, so the data is from five students in the *ScreenFlash* recorded group, and three who were not so recorded during the lesson.

Collecting further data

The sample of students from Centre A who were *ScreenFlash* recorded is assumed to be typical of the population of SNAB students who might carry out the *Acetabularia* tutorial. The test and written activities carried out by members of the class who were not *ScreenFlash* recorded acted as a check that the recorded students were not unusual within the group. Additional data from written questions, post-tutorial interviews and written tests also allowed features of interest found in the transcripts to be triangulated with evidence from different sources and from a larger sample of students.

For example, evidence of confusion about what *Acetabularia* is was first identified in the transcripts. Other evidence in the transcripts supports the idea that this confusion results in a barrier to drawing on relevant prior learning to make sense of the tutorial. Evidence supporting these findings was also identified in the written answers to questions and tests and in the post-tutorial interviews. Additional data collected from Centre B also served this purpose of triangulation, adding rigour and validity to this study.

In Centre B, pre-tutorial test data was collected from 37 students across two teaching groups with different teachers. The questions were identical to the test given in Centre A. Pre-tutorial test questions 3 and 4, which tested the knowledge introduced during the tutorial, were used a second time in Centre B, as a post-tutorial test (see Appendix 2).

Centre B students carried out the pre-test and post-test either side of the tutorial. The post-test included a question very similar to Centre A's Question 8, but which asked students to provide a conclusion and supporting evidence for each of the four Hammerling experiments. Students in centre B worked in pairs, so the learning situation was as similar as possible to centre A.

The data collection process is summarised in Table 3.2.

Table 3.2 Summary of data collected

Source of data	Sample size	Format of data
Test carried out before the tutorial.	17 from centre A 37 from centre B	Written test paper, questions 1-4.
Test carried out after the tutorial.	37 from centre B	Written test paper, same as questions 3 and 4 from pre-test, plus a question similar to Question 8 – see below.
Recordings of students carrying out the tutorial.	8 (four pairs) from centre A	ScreenFlash files showing screen activity and sound files of the recorded discussions.
Question 6 paper-based activity given out after Experiment 3 in the tutorial.	10 from centre A	Written experiment plans from 10 students, and recorded discussions of 8 of these students.
Question 8 paper-based activity given out on completion of the tutorial.	10 from centre A	Written answers from 10 students, and recorded discussions from 8 Centre A students.
Question 8 paper-based activity given out as part of the post-tutorial test.	37 from centre B	Written answers from 37 students. This question differs slightly from Question 8 given to Centre B students, as it asks students to provide a conclusion and supporting evidence for each of the four experiments.
Post tutorial interviews	8 from centre A	Recordings of discussions with students straight after the lesson where they completed the tutorial. Five of these students were from the group recorded as they carried out the tutorial. All of these students had carried out Questions 6 and 8 in addition to the pre-tutorial test.

3.3.3 Transcribing the recordings

Collection of recorded data through *ScreenFlash* software can be considered a relatively neutral activity, but it involves decisions about how many students to record, and the method used to select these students. In this study, selection of students to record was

random, using numbers from the class register, although the individuals selected could choose their partner to work with. No students declined. The number of recordings was limited to allow for detailed analysis within the scope of this study.

Students' discussion of the entire activity was recorded as they worked in their pairs. The recordings of the discussions during the tutorial and the post interviews were transcribed verbatim, using minimal punctuation. Long pauses were indicated with dotted lines. I either carried out the transcription personally, or checked transcripts made by assistants.

Transcription is an important stage of the methodology in this study, facilitating work on the content. It is part of the validation of theories that are put forward in the next two chapters. It allows others to view the data, and allows links to be made between assertions about the phenomena and exemplifications of evidence for the phenomena. Data from the recordings, written papers and tests was transcribed (*ScreenFlash* and audio) or scanned (written data), then interpreted and categorised to build inferences, as discussed in the next chapter.

3.4 Stage 3: Analysis of the data

3.4.1 The strategies available for analysis

Where recording and transcription could be regarded as relatively neutral activities, ambiguities come in the interpretation of the transcripts and written data. Visual clues and other events in the room provide context for what is being said, and these may be lost if analysis takes place after the event.

Grounded theory approaches use a systematic set of procedures to end with an inductively-derived explanation of phenomena. New theories emerge from data, the starting point for grounded theory, then more data is collected to test the new theories and to fill out the concepts and detail of theoretical points. The analysis is modified as a result of the new theories. More data is collected in an iterative cycle of refinements to the process. As there is a continuous interplay between data collection and analysis, the process is in strict contrast to the positivist hypothetico-deductive methodologies traditionally attributed to the natural sciences, and common in large scale studies (Gibbs, 2002).

ten Have (1999) formulated a strategy for exploring data through Conversational Analysis. He suggests starting with a complete recording of the event to be analysed, rather than

preselecting data in line with any expectations or hypothesis. He recommends making full transcriptions, even if simplified versions are produced later. Working through a sample of the data in terms of a defined set of 'organisations' is then recommended, using codings in a separate column or annotating the transcripts. After this preliminary process, a summary of observations should be made about the data, and any generalisations become a focus for continued analysis, while still keeping the original categories in mind. Further samples of data should then be analyzed using the same process, including making observations on the fit with the new, generalised categories. Each time more data is analyzed, the summary should be revised to fit the new data, while also commenting on variations and deviations from the general findings.

3.4.2 Strategies used for analysis in this study

In a similar process to that described by ten Have (1999) and the inductive process of grounded theorists, the analysis of the data in this study involved annotating and coding, referring to a model. The 'model' used in the initial stages of the study (developing the tutorial's task model) was the AAAS (2001) concept maps, which guided decomposition of the tasks in the tutorial. Once it had been developed, the task model of the tutorial became the 'basic model' against which the data was analysed. The initial analysis was also open, allowing the data to inform the task model where there was evidence of learning or barriers to learning which had not previously been identified.

Searching the transcripts and students' written work used both key words and interpretation of phrases. This analysis identified evidence for learning and evidence for barriers to learning associated with learning outcomes from the task model of the tutorial. For example, finding references to the words 'cell' and 'plant' provided evidence of the mental model students were using for the organism *Acetabularia*.

Evidence from the data contributed to the developing task model iteratively. For example, alternative use of 'cell' and 'plant' to refer to *Acetabularia* suggested that students were confused about what *Acetabularia* is. There was also evidence that students did not draw on relevant prior learning when making sense of the Hammerling experiments. This evidence was interpreted as a barrier to drawing on relevant prior learning about cells due to confusion about what *Acetabularia* is.

This interpretation of students' use of the terms 'cell' and 'plant' interchangeably in the data led to the inclusion of the context-specific idea 1 in the tutorial's task model: '*Acetabularia* is a single cell with specialised parts (hat, stem and rhizoid)'. Students' understanding of this

science idea may have been assumed in an analysis of the tutorial which aimed to produce a decomposed task model without reference to empirical data. This exemplifies the importance of using data in the process: it is only through using a resource in a genuine learning situation that some aspects of learning and barriers to learning are revealed.

Preliminary observations then led the next stage of analysis, where data was searched for further examples which supported the early generalisations and categorisations of the data. For example, the transcripts and written work were searched for evidence of the impact of confusion about *Acetabularia* on students' sense-making.

The mechanism used in the analysis was to organise the transcripts screen by screen, using the *ScreenFlash* recordings to link the data to screens where needed (Table 3.3). In this way, following ten Have's suggestion, this study explores 'the structural bases for the variations and the deviations in terms of the functionality of the basic model' (ten Have, 1999, p. 155).

3.4.3 Categorising the themes

Categorising the themes from the transcripts used annotations and sticky notes initially (see Figure 3.2). As themes started to emerge, keyword searches were used to find repeat instances of similar phrases, as described above. The hard copy written work from students was treated in a similar way.

The data was searched and categorised for matches with the task model for the tutorial. For example:

... yeah but we put the nucleus inside the thing, the stem, didn't we? [DM screen 21]
was categorised as evidence of learning background science idea 1): 'Cells contain specialised structures'.

DM's description of his plan for Question 6 is categorised under context idea 2): 'Acetabularia is ideal for this type of inquiry, because it is large enough to dissect and manipulate':

... we cut from there and then we suck the nucleus out and we just like leave that one to grow and we see if it grows or not without the nucleus. And then cut it from there again, and leave it with a nucleus and see if it grows to a full one. [DM planning the experiment in Question 6]

Barriers to learning were also matched with the task model categories. The following extract is categorised as evidence of a barrier to understanding background science idea 5): 'Development of characteristics (including specialised structures in the cell) is controlled by chemicals in the cytoplasm'. LF has developed the misconception that the presence of 'genetic

'material' in the tip explains the growth of an intermediate hat during Hammerling's Experiment 4 in the tutorial. She has not interpreted the observations using the idea that there are chemicals which communicate between the nucleus and the tip:

.... but we just said there is some genetic material in the tip. So when the genetic material in the tip and nuclei mix, they made this intermediate thingy. [LF discussing Question 8]

Assertions, articulation of what is happening, questions and responses, explanations and claims in the data provided specific evidence of learning, although it is also acknowledged that there is learning which is not necessarily evidenced. The data provide a window into students' thinking as they carry out the tutorial, but are likely to represent only a fraction of the thoughts involved in processing the tasks.

Figure 3.2 Initial analysis of transcripts using sticky notes

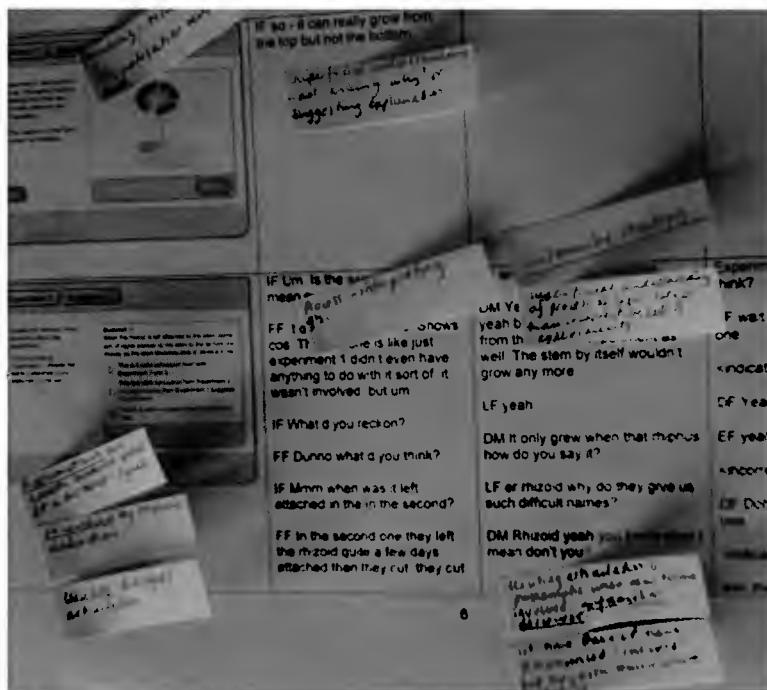
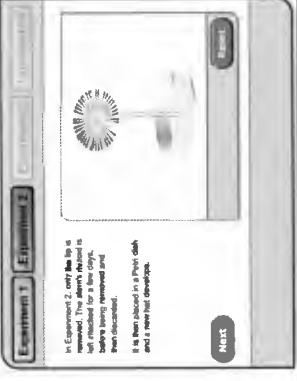


Table 3.3 An example of transcripts cut from screens 11 and 12

Screens 11 and 12	IF FF	LF DM	DF EF	IM SF
<p>IF So - it can really grow from the top but not the bottom.</p>  <p>In Experiment 2, only the tip is removed. The stem's height is left unchanged for a few days. Before being harvested and then collected in a plastic dish and a new root develops.</p> <p>Next</p>				<p>IM only the tip is moved. So it's grown back the tip. Right OK. That's grown a hat then.</p>
<p>IF Um. Is the second last two mean exactly the same?</p> <p>After the following press questions about the experiment, turning back to Experiment 1, I choose the correct one and then ask them to do the same for the last question.</p> <p>Question 1 When the rhiphus is left attached to the stem, some sort of signal passes up the stem to the tip from the rhiphus. So the stem becomes able to develop a hat. This is a valid conclusion from both Experiments 1 and 2. Question 2 There is a valid conclusion from Experiment 1, but not from Experiment 2. Question 3 There is a valid conclusion from Experiment 2 only. This is a valid conclusion from Experiment 2 only.</p> <p>Next</p>	<p>LF Ah I think it's the first one</p> <p>DM Yeah I think it's the first one, yeah because it was a conclusion from the second experiment as well. The stem by itself wouldn't grow any more.</p> <p>FF I dunno cos b is like. Shows cos. The last one is like just Experiment 1 I didn't even have anything to do with it sort of it wasn't involved but um</p> <p>LF Yeah</p> <p>IF What d'you reckon?</p> <p>FF Dunno what d'you think?</p> <p>IF Mmm when was it left attached in the in the second?</p>	<p>DF Experiment 2. What d'you think?</p> <p>EF Wait a sec. I think it's that one</p> <p>DF Yeah?</p> <p>EF yeah</p> <p>DF Doh. Maybe it's er that one. Well there's no like. What one? d'you think that one?</p> <p>LF Er rhiphus how do they give us such difficult names?</p>	<p>IM Um. Well we saw in the first experiment that SF The tip could grow a hat by itself</p> <p>IM Yes so it's not. This signal. That's not necessarily. So it doesn't, if the right one doesn't say that's incorrect.</p> <p>SF It just says it's</p> <p>IM Or does it? Cos it's valid from, difficult to tell or is it incorrect? Um</p> <p>EF Yeah</p> <p>DF Yey!</p>	

Barriers to learning were less easily identified from utterances and written data, as, even when students provided evidence of confusion or lack of understanding, the data did not always lead directly to inferences about where the problem lay. For example, in the post interview, DF is asked how a gene in the nucleus might affect the development of the hat. His response is that he 'can't explain'. This could be due to a failure to understand any one of the components of the science narrative which explains the link between genes and development, it may be due to a failure to link these ideas together successfully, or may be simply an inability to express his ideas as an explanation. For this reason, it was important to identify additional supporting evidence for initial interpretations of the data, as described earlier.

3.4.4 Producing generalisations from the data

Several themes emerged from the data as utterances were interpreted and generalised across the transcripts. These phenomena included students' reactions to the multiple choice questions, such as test-clicking to discover the answer before thinking about it in depth, the way students interacted with the manipulables and how students struggle with scientific terms in the tutorial. It was also noted that students kept well on task, with very little irrelevant talk. They were able to work through the tasks in the tutorial independently, with just a few episodes indicating frustration. (Episodes of frustration were treated as potentially significant, and were considered in the initial analysis.)

Once patterns started to emerge from the data, the generalisations about these patterns affected the searching process of further transcripts. Further evidence which fits the pattern of categories identified in earlier data are more likely to come to the attention of the researcher, so the process of identifying categories puts a bias on how the data is viewed (ten Have, 1999). But, the act of generalising and supporting the generalisations with selected data allows the data to be interpreted and inferences to be made.

For example, LF's utterance on Screen 1:

Oh it is a big cell

was categorised within context-based idea 1) from the task model: 'Acetabularia is a single cell with specialised parts (hat, stem and rhizoid)'. This utterance is interpreted as evidence that LF understands what she is looking at in the Screen 1 visual (and its associated text) (Figure 3.3).

Figure 3.3 Screen 1 of the *Acetabularia* tutorial

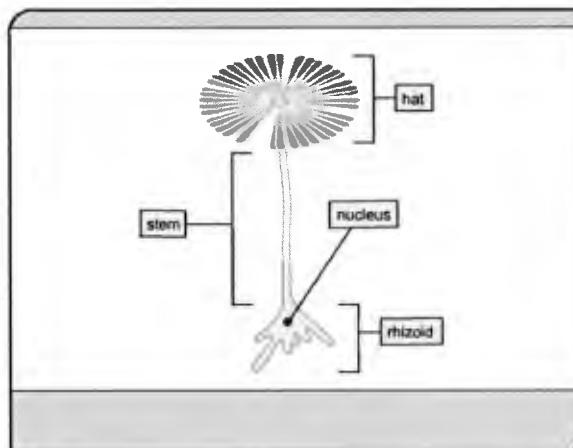
Acetabularia

Page 1 of 2

Next

Acetabularia is a green alga consisting of a single cell, 2-3 cm long. It has a rhizoid at one end, containing the nucleus, and a 'hat' at the other end.

Because it is such a large cell, it is possible to perform microsurgery on it, dissecting up the sections, and transferring the nucleus from one section to another. It has been used to study the role of the nucleus and cytoplasm in development.



Other utterances, such as “.... this is a cell, isn’t it?” and “There are two species of Ac the plant and the other plant” were identified suggesting students were not always sure about what *Acetabularia* is (see Section 4.2.2). ‘Confusion about *Acetabularia*’ became a new ‘barrier to learning’ category within Context-based idea 1, and data were actively searched for other phrases which could fit the category. In this way the analysis alternated between an inductive approach which suggests categories for analysis, and a deductive process which searched for data to corroborate the categories.

The search for data to support the category of ‘confusion about *Acetabularia*’, using key words such as ‘cell’, ‘plant’ and ‘alga’, revealed that students refer to the organism using all three of these terms indiscriminately.

3.4.5 Finding a focus for the study

The transcripts, backed up by the post-tutorial interviews and written test data, provide evidence of students’ learning remaining isolated where knowledge and understanding can’t be resituated into a new context. In particular, evidence of students’ confusion over what *Acetabularia* is raised the question of whether it matters that students think *Acetabularia* is a plant. Chapter 5 discusses the implications of this confusion in more detail. The question is

considered broadly, in terms of barriers to drawing on relevant prior learning to make sense of an inquiry.

As a theme which is potentially important to science education more broadly, the challenge of developing explanations was chosen as a focus for this study. Scaffolding explanations involves cuing and supporting the resituation of prior learning of background science ideas, and may also include developing these ideas or introducing new ones. This theme focuses the testing of Quintana *et al.*'s (2004) scaffolding strategies in Stage 4 of this study.

3.5 Stage 4: Testing the framework using the data

In the analysis and categorising of the data described above, the basic model which framed the analysis was the task model for the tutorial. In the fourth stage of this study, the Quintana *et al.* (2004) framework became the 'basic model' (ten Have, 1999) to be tested using the data. This stage tests whether the framework's scaffolding design strategies fit the scaffolding in the *Acetabularia* tutorial. Evidence for scaffolding in the tutorial is inferred from evidence of learning or barriers to learning in the empirical data.

The process used in Stage 4 was to compare the data, which was organised into evidence for learning and barriers to learning associated with the task model, with the framework' scaffolding strategies. For example, Guideline 7's Strategy 7d suggests that articulation and reflection should be encouraged around epistemic products of the discipline:

Strategy 7d: Highlight epistemic features of scientific practices and products.

(Quintana *et al.*, 2004, p. 373)

Examples of 'epistemic features and products' given in the Quintana *et al.* (2004) framework include 'explanations, descriptions and interpretations' (p. 371). Evidence assigned to the tutorial's task model category of 'interpreting scientific representations and models' provided evidence that the visuals and animations in the tutorial stimulate utterances about what *Acetabularia* is:

... so is this the same plant we're doing? [DM looking at a photograph of *Acetabularia* on the experiment selection screen]

and utterances which are observations of what is happening to *Acetabularia* in the experiments:

... so - it can really grow from the top but not the bottom. [IF screen 11].

The observed effect of the visuals and animations, in stimulating utterances, was not a specific design intention for these features. This comparison of the framework with the data suggests that guidelines could exemplify a greater range of artefacts which serve as epistemic products by embodying additional products of science, including visuals.

This analysis in stage 4 of the study identified the nature of the scaffolding in the tutorial, by comparing features of the tutorial with Quintana *et al.*'s (2004) guidelines. Deviations from the guidelines in the framework were identified in the tutorial using the data. This stage also identified gaps where the data suggested more scaffolding was needed in the tutorial.

Testing the framework in this way highlights where the framework did not provide sufficiently detailed guidance for analysis of the scaffolding in the tutorial, or for development of further scaffolding to address the needs of learners identified from the data. Gaps in the framework identified in the analysis included the suggestion that the scaffolding of background science ideas is important in addition to scaffolding the inquiry processes.

3.6 Stages 5 and 6: Recommendations and evaluation

The fifth stage of the study distinguishes it from straightforward educational research. This stage uses the analysis and theorising to infer revisions needed to both the framework and the tutorial (see Section 6.7.1). It suggests principled, theory-based designs for new or revised tutorial screens, and attempts to put Quintana *et al.*'s (2004) scaffolding design guidelines within a broader model of pedagogy for science inquiry learning (Section 6.6.1). Finally, Chapter 7 provides a critical review of the study and suggestions for further work.

This chapter has described the methods used to collect and analyse the data, and the stages involved in the study. It described how the analysis leads to inferences being made for how the scope of the Quintana *et al.* (*ibid*) framework could be broadened using the example of the *Acetabularia* tutorial, and how the tutorial could be revised. The final section in this chapter discusses the ethical considerations of the study.

3.7 Ethical considerations

The data collection sessions in this study conformed to the ethical guidelines of the British Educational Research Association (BERA, 2011). All research instruments and protocols were assessed and approved by the Institute of Education's Faculty Ethics Committee. Ethical considerations include informed and voluntary consent from all participants and a clear understanding of their right to withdraw at any stage of the research process. Participants were assured of anonymity and privacy.

The institutions where data was collected were chosen because they were SNAB centres which had taught the course for at least two years by the start of this data collection. The centres were keen to be involved with research into SNAB tutorials, and valued this contact with the project.

Students who took part in the study were not disadvantaged, as recordings took place in normal lesson time, in the lesson where the activity being studied was planned to take place in the scheme of work.

Students and their parents gave informed consent for use of the data. A letter went to students and parents explaining the purpose of the research (see Appendix 5). Students gave signed consent for use of anonymised data, and were given an opportunity to opt out of the study at the start and end of the process.

The centres' identities are hidden and student data is anonymised with code names. Codes run alphabetically, using F for female and M for male students. For example, one pair of female students were labelled FF and IF. A mixed pair were LF and DM.

Personal data was collected directly from the students, or provided by the teacher with the students' permission. It was made clear to the students that this information would not be used in any way to identify them. It was also explained to students that they were giving permission for the anonymised data to be published in future reports of this study.

3.8 Conclusions from this chapter

This study blends methodologies from educational research and educational design to fit the purpose, and shows a self-conscious awareness of my position as both developer and evaluator of an educational resource (Miles and Huberman, 1994). Categories determined by an inductive analysis of the tutorial and data were then used in a deductive analysis of learning and barriers to learning evidenced in the data. This categorisation of the data introduced a degree of objectivity, allowing comparisons between students and between different screens in the tutorial. It may, though, have missed subtleties in differences between subjects in an attempt to generalise about their similarities. Recognising that there was data of interest which did not fit the categories of learning and barriers to learning described in the task model in the first stage of analysis, a more grounded, inductive approach also identified barriers to learning which refined the task model categories iteratively throughout the analysis.

While aiming to make my methods transparent for the purposes of validity, I have been open to the most appropriate approaches to allow an iterative process of interrogating and analysing the data, and searching for patterns and phenomena. The approaches I used have been influenced by social constructivist theories of learning, and psychological studies connected with positive and negative effects of the design of learning resources.

The later stages of the study tested the Quintana *et al.* (2004) framework against the data, and identified phenomena which did and which did not fit the framework. Through this approach, gaps in the framework were identified, in the area of scaffolding background science, for example. Identifying data which does not fit with the framework may not have occurred if the analysis task simply involved matching data to the barriers to learning underpinning the scaffolding strategies in the framework.

This study focuses on one advanced level biology activity, to establish an approach to iterative design using a previously developed scaffolding design framework and empirical data. The scope of this research is limited to learning through the particular features in the tutorial, and to the specific domain of learning background science ideas, but demonstrates a process which could be used more broadly.

The next chapter sets out the data which provides evidence of the learning and barriers to learning relevant to developing explanations in the *Acetabularia* tutorial.

Chapter 4 Analysing the data using the tutorial's task model

The analysis of the data in this chapter follows the stages of the methodology described in Chapter 3. The task model for the SNAB *Acetabularia* tutorial was set out in Section 3.2.1. Following a summary of the evidence of prior learning from the pre-tutorial tests (Section 4.1), the analysis compares the data with the three categories of learning outcomes in the task model: background science, context-based science and science inquiry processes. The data is used as evidence for students achieving these learning outcomes, although inferences are also made about the learning processes taking place. For example, section 4.2.1 organises the data according to the learning outcomes in the task model relating to background science. In the first section, the data used as evidence for the learning outcome 1: 'Cells contain specialised structures' was also discussed in terms of learning processes: 'students were able to resituate prior learning about the nucleus as a specialised cell part to the new context of the *Acetabularia* cell'.

4.1 Evidence for prior learning

The pre-tutorial test used in this study assessed some aspects of students' relevant prior learning before they carried out the tutorial (see Appendix 1). This test of prior learning provides a baseline to compare with evidence of learning as students carry out the tutorial.

Students' responses to Question 1 of the pre-tutorial test 'What is a gene?' were frequently deterministic, describing characteristics which are inherited with certain genes. These extracts use students' own spelling, as do all later quotations from written answers:

A gene is an attribute handed down from parents. [EM's written answer to pre-tutorial test Question 1]

... defines your look, personality etc. [AM's written answer to pre-tutorial test Question 1]

The following responses were given to pre-tutorial test Question 2 'Where would you find genes in a plant or animal cell?' It can be concluded from this data that students make the link between genes and the nucleus, and that genes are associated with DNA. These responses to

Question 2 are representative across students from Centres A and B. All of the 54 students who took the pre-tutorial test were able to describe where genes are in a cell:

- In the cells, nucleus.
- In the nucleus of cells on the DNA strands
- In the nucleus of every cell.
- In the DNA
- DNA (nuclei)
- In both plants + animal cells in the nucleus.

Across answers to several of the pre-tutorial test questions, students demonstrate they have a notion of genes controlling cell processes:

A piece of information that is inherited from your parents that determines what characteristics you have. [IF written pre-tutorial test Question 1]

They decide everything. [IF written answer to pre-tutorial test Question 3]

Depending on what the genes code interpret into, depends on the make up of cells. [AM written answer to pre-tutorial test Question 4]

The gene tells the cell what type of cell it is [IF written answer to pre-tutorial test Question 4]

There is little evidence that students can explain the control of cell processes at the level of causal mechanisms, or that they understand the link between genes and functions in the cell. The pre-tutorial test Question 3 asks 'Explain how genes affect processes taking place in the cell'. Thirteen out of 54 students gave either no answer at all, or an inadequate answer. Of the students who made a reasonable attempt at Question 3, eight students linked genes with characteristics or malfunctions, without explaining the mechanism:

... some genes can be faulty and cause problems like a malfunctioning CFTR protein. [XF pre-tutorial test Question 3]

Genes tell a cell what sort of a cell its meant to be e.g. blue eyes gene tells the cell to be blue. [LF pre-tutorial test Question 3]

Abnormal genes may cause some processes to function abnormally ... [IF written answer to pre-tutorial test Question 3]

Other students referred vaguely to mechanisms for the control of cell processes, including descriptions of 'information', 'instructions', and 'chemicals':

They affect processes in the cell as they have instructions that have to be carried out. [HF written answer to pre-tutorial test Question 3]

Only 7/54 students referred to protein synthesis or transcription and translation to explain control of cell process:

DNA is transcribed into mRNA which sends messages to different part of the cell via tRNA. [LM written answer to pre-tutorial test Question 3]

Pre-tutorial test Question 4 asked more specifically about how a gene 'might influence development of a remote part of a cell...' This question tests knowledge and understanding which should be developed as students carry out the *Acetabularia* tutorial. They previously learnt about protein synthesis in the context of inheritance of cystic fibrosis.

Fifteen out of 54 students did not provide an answer to this question. Only 13/54 students drew on the idea of protein synthesis or transcription and translation. These were though, mainly vague references to proteins and protein structure without making the link between production of proteins and development:

It will tell the mRNA and tRNA what protein to produce.

... the shape of a protein affects the shape of the cell it makes.

Only one student gave a summary which makes links between a range of ideas that explain how genes communicate with remote parts of a cell, although even here there is no specific link to development:

Genes are transcribed on to RNA and are taken out of the cell though a nuclear pore, the information is then translated on a ribosome + this information /protein can be transferred via vesicles to other parts of the cell.

In the previous SNAB topic (Topic 2), students learnt about development in the context of the faulty CFTR gene. Topic 3 refers to development in the context of a cell developing into a multicellular organism. The evidence from this study suggests that the concept of development is not familiar to students in the context of an individual cell developing into a specialised cell.

Due to the emphasis in Topic 2 on phenotype as a result of a faulty gene (although there is some discussion in this chapter on the effect of the CF allele on translation), students may

associate genes with effects on the whole organism rather than processes within individual cells. It appears that the questions in the pre-tutorial test fail to trigger explanations based on relevant prior learning in most cases because they ask about the role of genes in 'cells'. There is little evidence in the pre-tutorial tests that students resituate their knowledge of protein synthesis to answer the question about control of processes or development in cells. The CFTR context is referred to directly by one student (XF), quoted above. This is evidence that students have been introduced to relevant background knowledge which could help to explain cell development if they were able to resituate this learning.

Some students provide evidence of misconceptions in the pre-tutorial tests, which could explain their later confusion or failure to make sense of the tutorial in terms of their prior knowledge. Evidence of misconceptions appears in quotes from the data earlier in this section, for example about the action of genes and determinism. In addition to these, the following responses exemplify some specific misconceptions:

... the DNA which make up the gene, contain a 3D structure due to amino acids within the DNA which contain hydrogen bonds that determine the overall structure of the cell and therefore the shape etc.

Genes can change size and shape within a nucleus ...

Genes can speed up, slow or change reactions ...

... the way a gene bonds with another determines the shape and amount of folding ...

... furthermore, genes contain proteins - it's these proteins that determine the way in which the bonds hold the structure together.

If, as these examples suggest, some students are confused about the basic scientific ideas behind the control of cell processes by genes, including confusion between genes and proteins, they will lack the background science foundations on which to build explanations of control of development. This potential barrier to learning was discussed in terms of the literature on misconceptions in science education in Section 2.5.3.

The *Acetabularia* tutorial assumes knowledge of basic cell structure and function, genes and gene function. Students have studied DNA structure and protein synthesis in a previous topic, so it could be expected that they make links between genes and proteins made in the cell.

It can be concluded from the evidence of the pre-tutorial test, that the majority of students demonstrate prior learning from GCSE and the earlier SNAB topics which includes:

- knowledge of basic cell structure
- an awareness that the genes are in the nucleus
- ideas about inheritance and phenotype.

Only a minority of students have knowledge of:

- the role of genes in the control of cell processes
- a link between genes and proteins produced in a cell.

There is no evidence that students make the association between genes, proteins, processes being carried out in the cytoplasm and development of the cell, and there is evidence of widespread misconceptions about gene structure and function. The implications of these findings are that prior learning which is relevant to understanding development in *Acetabularia* can't be assumed in students carrying out the tutorial. This finding is addressed in the discussion of revisions to the tutorial in Chapter 6.

4.2 Evidence of learning from the tutorial

The next stage in this study involved identifying evidence of learning and barriers to learning from the *Acetabularia* tutorial. The task model set out in Section 3.2.1 provided a categorisation for this evidence. The efficacy of the scaffolding in the tutorial can be inferred from the data demonstrating learning and barriers to learning, when considered alongside evidence of prior learning.

Where it is necessary to put exemplar data in the following sections into context, the tutorial's screens or tasks are described. The evidence also refers back to pre-tutorial test data, and evidence from the post-tutorial tests and interviews. Written answers to the paper-based questions (6 and 8) described in Section 3.3 are also drawn upon. In the following sections, these are referred to simply as Question 6 or Question 8.

The following sections provide some selected student data for illustration. Further tabulated examples of data are available in the Appendices 6-8. This avoids lengthy examples of student data detracting from the thread of the main ideas in the chapter. The tables in the Appendices also provide some semi-quantitative summaries to give an indication of the incidence of a specific category of evidence. Each section below corresponds to a table in the Appendices, and

summarises the evidence for learning and barriers to learning associated with one of the categories in the tutorial's task model.

4.2.1 Background science

Summary of learning and barriers to learning about background science ideas

The following analysis relates to the data categorised as background science content in the task model for the *Acetabularia* tutorial (see Section 3.2.1). Additional examples of data relating to background science are available in Appendix 6.

1. Cells contain specialised structures

Evidence from the pre-tutorial tests demonstrated that students have knowledge of the nucleus as the structure containing genes in a cell, and some knowledge of the function of genes (Section 4.1). The transcripts show that students refer to the nucleus of *Acetabularia* confidently when carrying out the manipulable (interactive, drag and drop animations) of nuclear transplant in the tutorial:

... so that's the acet abubba that has the nucleus so prepare to get dragged... [LF screen 4]

... click on the nucleus. Oh I get it. There you go. [DF screen 18]

... yeah but we put the nucleus inside the thing, the stem, didn't we? [DM screen 21]

The transcript data, backed up by the written data, suggests that students were able to reattribute prior learning about the nucleus as a specialised cell part to the new context of the *Acetabularia* cell. All ten students who carried out Question 6 represented the nucleus in their experiment plans, and referred to manipulating the nucleus as part of the experiment.

2. The nucleus contains the cell's genetic material

In their discussion of Question 8, all (8) recorded students refer to 'nucleus' repeatedly. In the following extract, LF and DM discuss how Experiment 3 shows the genetic material is in the nucleus as they link conclusions and evidence in Question 8:

DM ... we can say like all genetic material is contained in the nucleus

LF Yeah

DM And then we can say Experiment 2 because or was it Experiment 3? Because

LF It was Experiment 3

DM Yeah Experiment 3 because we put the nucleus into the stem grew into a full
LF A whole new cell.

The transcript evidence suggests that students understand that the nucleus contains the cell's genetic material. This is supported by written evidence to Question 8, where 41/47 students produced conclusions using this knowledge. Knowledge and understanding about the nucleus evident in the pre-tutorial tests appears to be applied to the context of *Acetabularia*.

However, in the Centre B post-tutorial tests, there is a question similar to Centre A's Question 8 asking for conclusions and supporting evidence for each experiment. The responses for Experiment 4 demonstrate confusion about what Experiment 4 shows. Ten of the 36 students who gave responses suggested that there is genetic material in other parts of the cell:

Genetic material is formed in the nucleus but is transferred and then carried by the stem.

This suggests that not all students are scaffolded to develop the correct conclusions from the experiments in the tutorial and that the scaffolding does not avoid misconceptions being introduced.

3. The genetic material contains the code that controls which proteins (and other chemicals) are made in the cytoplasm

In the pre-tutorial test, students describe genes mainly in terms of inherited characteristics. Some students mention the genetic code, but do not link this with proteins or other chemicals made in the cell.

As they work through the tutorial, students discuss chemicals in the cytoplasm in terms of where these are stored and whether the signal between nucleus and tip is chemical or electrical (also see transcript excerpts under point 4. below). Students do not suggest that these chemicals are produced by transcription and translation during their discussions of the tutorial or the paper-based tasks in questions 6 and 8. Neither do they make reference to the nucleus controlling which chemicals are made in the cytoplasm.

The evidence from the post-tutorial tests suggests that a minority of students refer to transcription and translation and protein synthesis in the context of explaining development in *Acetabularia*. Only 8/37 students explicitly made the link between the genetic code and chemicals in the cytoplasm, and 12/37 made the link between transcription and translation and

development. There is no evidence that students associate the controlling chemicals referred to in the tutorial with transcription and translation, or that they consider these chemicals have any relationship with proteins produced through transcription and translation.

4. Chemicals in the cytoplasm control the cell's activities (which chemical reactions take place)

In Experiment 4 of the tutorial, students discover that swapping nuclei between two species of *Acetabularia* results in development of a hat that matches the nucleus present. The *ScreenFlash* recordings show that, in the task following Experiment 4, all the (8) students who were recorded carrying out the tutorial correctly matched three conclusions with statements describing two stages of the experiment (Figure 4.1):

... cos it was like the nucleus was what the other hat grew. [Transcript of IF justifying her answer to the question after Experiment 4]

Figure 4.1 Screen 30: Question after Experiment 4, matching statements to evidence

Experiment 1 Experiment 2 Experiment 3 Experiment 4

Experiment 4 was in two stages:

1. The stems were switched and an intermediate hat grew from the tip;
2. The hats were removed and a new hat corresponding to the species of the nucleus grew.

Type into the boxes the number of the stage (1 or 2) which you think provides evidence to support the following conclusions from Experiment 4:

the nucleus determines which hat develops

the cytoplasm contains chemical signals which influence hat development

the chemical signals present in the cytoplasm are determined by the nucleus

Submit

This task involves interpreting the experiment in terms of chemical signals present in the cytoplasm affecting development. IM and SF justify their choice of answer to this question. They refer to chemical signals ("that") being present in the cytoplasm from the original nucleus:

IM ... that could still be there from before, from the original ...

SF ... from the original nucleus and then once you've replaced it and it's sort of had time to grow the new signal's sent by the new nuclei. [IM and SF justifying answer to question after Experiment 4]

In the post-tutorial interview, AM and IF use the idea of chemicals in the stem when explaining development of the intermediate hat in Experiment 4:

... then the green hat grew cos there were still chemicals in the stem. [AM post-interview]

... already chemicals in the stem that come from the nucleus. [IF post-interview]

All the written answers to the paper based questions 6 and 8 show some evidence that students understand the controlling role of the nucleus. Evidence from the post-tutorial tests from Centre B supports this conclusion from the written answers (35/37 students).

Fewer than half (13/37) the students provided direct evidence in the post-tutorial tests that they understand that chemicals in the cytoplasm exert control on cell processes.

The conclusion from this data is that students are prompted to explain the experiments in terms of chemicals in the cytoplasm by the multiple choice questions in the tutorial, but they do not necessarily draw on this idea when explaining control by the nucleus in later problems. The complete 'story' of nucleus → chemicals in the cytoplasm → control of cell processes is not evident in students' post-tutorial accounts.

5. Development of characteristics (including specialised structures in the cell) is controlled by chemicals in the cytoplasm

There is evidence that the first Hammerling experiments in the tutorial are successful in introducing the idea that specialised parts grow if the nucleus is present, or if it has been left to exert its influence by leaving the rhizoid attached to the stem for a few days. The transcripts show that students refer to the link between the nucleus and development of specialised structures when planning their experiments in Question 6:

FF ... cos this like, can grow a hat and whatever, but it can't grow the rhizoid bit at the bottom. And this can grow into a full plant cos it's got like the nucleus and that, isn't it?

IF Yep. So when the stem had a nucleus it grew like the rhizoid as well. [FF and IF discussing the earlier experiments during Question 6 planning].

... then they took the nucleus, then like put it in the stem, and the stem grew a new rhizoid and hat thing. [DM Question 6 discussion].

Knowledge that the nucleus needs to be present for development of new cell parts is demonstrated in the written answers to Question 6. All ten Centre A students showed evidence of understanding the link between the nucleus and development.

The process by which the nucleus determines proteins produced in the cytoplasm (transcription and translation) was introduced to students in the previous topic in the context of cystic fibrosis, along with the link between genes and phenotype. This study suggests that students carrying out the *Acetabularia* tutorial do not resituate this learning to make the link between genes and development of a single cell. As a result, they are not sure of the nature of the chemicals in the cytoplasm referred to in the tutorial, or how the nucleus exerts control:

... (DNA) sends stuff out. It like comes out of the nucleus. [DF post-tutorial interview]

...does the nucleus like affect the development of the tip, which controls how the hat works? [EF post-tutorial interview]

The post-tutorial interview data shows how some students remember that the nucleus controls development, but are unsure of, or are vague about the mechanism. This supports the conclusion that students are not able to explain the mechanism of how the nucleus exerts control:

Interviewer: ... how might a gene down there in the nucleus affect the development of the hat?

DF I don't know, it's really hard to explain, it like influences what happens there or something.

Interviewer: Yes, And how does it do that?

DF It um dunno I can't explain. [post-interview with DF]

A comparison of pre-tutorial test answers and answers in the post-tutorial test provides evidence that some students' explanations become less inclined to draw on causal mechanisms after the tutorial. For example, students' responses become more contextualised, referring to the more visible external effects of development (hat developing) rather than explanations at the molecular level (protein synthesis). This shows that students' explanations do not always build on the knowledge evidenced in the pre-tutorial tests, as shown in the following example:

pre-tutorial: genes are transcribed onto RNA and are taken out of the cell through a nuclear pore, the information is then translated on a ribosome + this information, protein can be transported via vesicles to other parts of the cell.

post-tutorial: ... the experiments suggested that the signal between the rhizoid + stem is probably chemical rather than electrical → chemically sent to other parts of the cell (information) to tell it how to grow and develop.

Twelve students from Centre B produced a pre-tutorial test explanation of the role of genes in development using a description of protein synthesis. Of these 12, four produced post-tutorial test answers which were less sophisticated or more confused.

In addition, there is evidence in the post-tutorial tests that some misconceptions have been introduced as students try to process the tutorial in the light of their previous knowledge:

... genes affect different parts of a cell depending on where they are found

There is evidence of confusion about whether the nucleus is part of a cell or a multicellular organism:

... in a plant the stem may produce a new head/ hat due to the chemical signal from the nucleus containing the genes.

As a result of this confusion, the link between gene action in cells and in whole organisms is confused.

The written evidence from Question 8 suggests that the link between chemicals in the cytoplasm and development is not necessarily robust. Twenty-eight out of 47 students specifically make this link in written answers to Question 8, for example:

“... it sends signals in the cytoplasm for new hats and rhizoids....”

and only 10/37 made this link in the post-tutorial tests. The written evidence under Background Science points 3 and 4, set out in Appendix 6 also supports the idea that some students are confused about what the chemicals being referred to are, so fail to make the link between transcription and translation, the chemicals in the cytoplasm and development.

4.2.2 Context-specific learning

Evidence for learning and barriers to learning contextual ideas relating to *Acetabularia* and the Hammerling experiments is organised below according to the task model categories. Further examples of data relating to contextual science ideas are provided in Appendix 7.

1. *Acetabularia* is a single cell with specialised parts (hat, stem and rhizoid)

The evidence for students' knowledge of the parts of *Acetabularia* occurs throughout the transcripts, the written answers to questions 6 and 8 and the post interviews.

The *ScreenFlash* videos of students' on-screen actions provide evidence that students have linked the names of the parts to the visual of *Acetabularia*. Students follow the instructions to click on or drag specific named parts of *Acetabularia* in the drag and drop manipulables of the Hammerling experiments. In the example below, DF recognises the nucleus and clicks on it in screen 18:

Click on the nucleus. Oh I get it. There you go.

However, the transcripts show that some students struggle with the names of the specialised parts of *Acetabularia*:

DM ... it only grew when that rhiphus how do you say it?

LF er rhizoid. Why do they give us such difficult names? [DM and LF screen 12]

The use of unfamiliar scientific terms in the tutorial is a possible barrier to learning. The following extracts from transcripts of the students' discussions show how students refer to specialised parts of *Acetabularia* with more confidence in the later tasks in the tutorial:

... in the second one they left the rhizoid quite a few days attached then they cut off the hat didn't they? [FF screen 12]

... so in the second experiment did the tip grow a hat? [LF screen 14]

... you cut the rhizoid off and the stem did grow. [HF post-tutorial interview]

This evidence suggests that students recognise cell structures in the context of *Acetabularia*, and that through using the names of the specialised structures of *Acetabularia*, they learn these as the tutorial proceeds.

These conclusions are supported by the written answers to Questions 6 and 8. In Question 6, 7/10 students referred to 'hat', 8/10 referred to 'stem', 3/10 referred to 'tip', 6/10 referred to 'rhizoid' and 10/10 referred to 'nucleus' correctly in their experiment plans, with no evidence of incorrect use of these terms. In the 47 Question 8 scripts, 44 students refer correctly to

'rhizoid', 47 refer to 'hat', 44 refer to 'stem', 44 refer to 'nucleus' and 37 refer to 'tip' in their conclusions from the experiments.

Data referred to under Context Specific Learning point 1 also includes the knowledge and understanding of what *Acetabularia* is. Relevant evidence of students' ideas includes statements demonstrating understanding of *Acetabularia* as a cell, and also *Acetabularia* as a plant.

Students refer to *Acetabularia* as a 'cell' throughout the tutorial:

Oh it is a big cell. [LF screen 1]

... right so we start off with our two little cells. [DF Question 6 transcript]

... a complete cell could grow from the stem. [IF Question 8 transcript]

The transcripts show how students also refer to *Acetabularia* as a plant throughout the tutorial.

This is an incorrect categorisation of *Acetabularia*:

... so is this the same plant we're doing? [DM]

... and this can grow into a full plant. [FF]

... there are two species of Ac the plant and the other plant. [DF]

The written answers to Question 6 also show references to *Acetabularia* as an alga, plant and cell. Both 'cell' and 'alga' are correct descriptions of *Acetabularia*. Four out of ten students referred to *Acetabularia* as a cell consistently in their answers.

There were still some references to *Acetabularia* as a plant by the time students got to Question 8, but students refer more consistently to 'cell' by this stage. In the 47 written answers to Question 8, 20 students referred to 'cell' consistently, one referred to both 'cell' and 'alga', three referred to 'plant' consistently, three referred to both 'cell' and 'plant'.

In the post-interviews, students continued to alternate between the three ways of describing *Acetabularia*:

... the cell was cut into three parts and the tip grew a hat the nucleus part grew into a full cell again. [JF describing experiment 1]

... they like cut the cell into three sections. [FF describing experiment 1]

... it grew a whole new plant. [EF describing experiment 1]

... they brought that algae and cut it up into three sections. [EF describing experiment 1]

The data shows that, although there is a trend towards more frequent use of 'cell' to describe *Acetabularia* as the tutorial proceeds, individual students vary between these different ways of describing the organism. From the transcripts and written answers of three individual students, the following samples of references to *Acetabularia* are arranged in chronological order to illustrate this:

LF

Oh it is a big cell. [screen 1]

Remove rhizoids from rest of cell. [written answer Question 6]

... grew into a complete plant. [written answer Question 8]

... these little weird flower thingies, they're cells are they? [transcript Question 8]

... grew into a complete cell. [written answer Question 8]

DM

... so is this the same plant we're doing? [screen 7]

... the thing on the computer on the Acet. whatever it's called. [Question 6 transcript]

the nucleus controls development in the cell. [written answer Question 6]

The stem grew to a complete plant. [written answer Question 8]

... it was cut from the rest of the cell. [written answer Question 8]

DF

... right so we start off with our two little cells. [DF Question 6 transcript]

There are two species of Ac the plant and the other plant. [Question 6 transcript]

Cut the hat and rhizoid off the alga. [written answer to Question 6]

The nucleus was able to reform all parts of the cell.... [written answer Question 8]

... he cut the end of the nucleus off of two different types of alga. [describing Experiment 4 in post-interview]

The data shows that the same students confidently refer to specialised cell parts of *Acetabularia*, such as the nucleus, then later refer to *Acetabularia* as a plant. Some examples of this are shown in Table 4.1.

Table 4.1 Data showing references to cell parts and to *Acetabularia* as a plant

Reference to nucleus	Later reference to 'plant' by the same student
“ ...click on the nucleus. Oh I get it. There you go.” [DF carrying out the manipulable, screen 18 transcript]	“ ...there are two species of Ac the plant and the other plant.” [DF Question 6 transcript]
“... all the genetic material is contained in the nucleus” [EF written conclusion in Question 8]	“... both plants grew with the same hat...” [EF written answer Question 8]
“....we could probably like put a nucleus inside the stem as well couldn't we?” [DM Question 6 transcript]	“... the stem grew into a complete plant....” [DM written answer Question 8]
“...you cut it into the 3 bits and try and grow them all like from about the nucleus.” [FF Question 6 transcript]	“...and this can grow into a full plant.” [FF transcript Question 6]

It can be concluded that students use parallel, conflicting models for *Acetabularia*. The significance of this confusion is that potentially it could present a barrier to making inferences from the Hammerling experiments about cells more generally.

2. *Acetabularia* is ideal for this type of inquiry, because it is large enough to dissect and manipulate

There is evidence that students learn the techniques and processes of the Hammerling experiments effectively through the tutorial. They appreciate that *Acetabularia* can be cut up and manipulated, even though they are unsure what type of organism it is:

... but we put the nucleus inside the thing, the stem, didn't we? [DM screen 21]

... we cut from there and then we suck the nucleus out and we just like leave that one to grow and we see if it grows or not without the nucleus. And then cut it from there again, and

leave it with a nucleus and see if it grows to a full one. [DM planning the experiment in Question 6]

... so you chop that bit and that bit and that bit off, so you are left with the stems of both of them, then you put the nucleus from that one into that and you put the nucleus from that one into that stem. [DF planning the experiment in Question 6]

In Question 6, the task is to use two species of *Acetabularia* with different shaped hats to explore the role of the nucleus in development. All ten written answers show that students are able to plan an experiment to test a hypothesis, and can apply the techniques from the first three Hammerling experiments presented in the tutorial.

Students also show evidence of understanding the logic of Hammerling's inquiry:

DF ... why's it chopping off?

EF to see what hat will grow there. [DF and EF discussing Experiment 4]

... d'you reckon, cos like they'd all be damaged wouldn't they? [FF uses logic to reject an incorrect conclusion after Experiment 1]

... the end of the first one didn't actually have a bottom bit but it still grew a hat. [LF compares Experiments 1 and 2]

It can be concluded that students understand the aims and logic of the Hammerling experiments. They become familiar with the techniques used in the experiments, and can apply the reasoning used in the inquiry in a new situation (Question 6 experiment planning).

3. A complete cell develops from any cell part that has the nucleus present, or from parts to which the rhizoid containing the nucleus has remained attached after removal of the hat

Understanding the idea that the nucleus must be present or the rhizoid must remain attached for specialised parts to develop is evident in the transcript data. The excerpts of data from Background Science points 4. and 5. support this idea. The written evidence supporting this idea has also been discussed under Background Science Ideas, point 4. This data showed that 35/37 Centre B students used the idea of the controlling role of the nucleus in their answers to the post-tutorial test:

DM Why doesn't the stem get?

LF Because it's like just the middle bit, it doesn't have any information or anything. [Screen 5: DM and LF discuss the fact that the stem without the nucleus present does not develop]

... they took the nucleus, then like put it in the stem, and the stem grew a new rhizoid and hat thing. [DM discussing Question 6]

... because it was able to re- like grow all parts of the cell again ... [Question 8 transcript: DF explaining the evidence for the idea that the nucleus contains the genetic material]

Students also refer to the rhizoid's role, referring to the evidence from Hammerling's earlier experiments:

FF In the second one they left the rhizoid quite a few days attached then they cut, they cut off the hat didn't they?

IF Yeah

FF And it grew from the stem. [Screen 12: FF and IF discuss Experiment 2]

In the written answers to Question 8, 35/47 students produced conclusions backed by evidence which referred to the rhizoid as determining development in *Acetabularia*. For example:

When the rhizoid is attached to the stem a signal passed up the stem to the tip – influence seen after it is cut off

The data shows that the link between the rhizoid and development is established through the tutorial, and that students link the presence of the nucleus or the rhizoid with development of a complete *Acetabularia* cell.

4. A chemical signal travels between the nucleus and the cytoplasm, and these chemicals in the cytoplasm determine development of the cell parts

There is evidence that students understand that the nucleus controls development of specialised parts, and that there are chemicals in the cytoplasm which affect development. Other examples show students are not clear about the difference between 'genetic material' and the chemicals in the cytoplasm. The relevant evidence for this has already been discussed under Background science Point 5.

The evidence in this section about contextualised science ideas backs up the conclusions in the previous section on background science ideas. Students can follow the reasoning of the

Hammerling inquiry, leading to conclusions about which part of the cell controls development. They also follow the logic in the multiple choice questions, leading to the idea that there is a chemical signal between the nucleus and the tip of *Acetabularia*. There is, though, no evidence that students draw on their prior learning about protein synthesis in cells as they make sense of the tutorial. The evidence supports the idea that confusion about what *Acetabularia* is may contribute to a barrier to resituating relevant background science from previous topics associated with genetics and cell biology.

4.2.3 Skills used in scientific inquiry processes

There is evidence that students carry out scientific inquiry skills as they engage with the processes of the Hammerling experiments. The data analysis below is organised according to the task model categories described in 3.2.1. Further data relating to inquiry processes is in Appendix 8.

I. Analyzing data (observations)

The data in the tutorial consists of observations of the outcomes of the Hammerling experiments from the animations. There is evidence set out in Section 4.2.1 supporting the idea that students interpret familiar cell structures such as the nucleus when these appear in the context of *Acetabularia*.

Students comment on or recall what they observe as the animations show *Acetabularia* developing, for example. These utterances show an ability to draw out the salient inferences from the data, which consists of observations from the Hammerling experiments:

... so - it can really grow from the top but not the bottom. [IF screen 11]

.... the end of the first one didn't actually have a bottom bit but it still grew a hat. [LF screen 12]

Post-tutorial interview data shows that students recall the Hammerling experiments accurately:

... on the fourth experiment they, they chopped the rhizoid off both the green and the red plants and swapped them over and um when they swapped the green one over to the red plant the green hat no the red hat still grew for the first time then they chopped that off and then the green hat grew cos there were still chemicals in the stem ... [AM post-tutorial interview]

The written evidence from all ten students who carried out Question 6 shows that they can reproduce images (see Appendix 9 and Appendix 10, scans of students' experiment plans) and apply the processes shown in the animations of the experiments in the tutorial in the new context of their own experiment plans.

The data suggest that the tutorial is successful in providing a narrative of the Hammerling experiments, allowing students to make observations about the outcomes, and to make inferences from these observations.

2. Constructing explanations

Students start to construct inferences that make sense of what is happening in the experiments as they discuss the experiments shown in the tutorial:

... because it's like just the middle bit, it doesn't have any information or anything. [LF explains why the stem does not develop in Experiment 1].

The data provides evidence that students discuss the conclusions as they work through the multiple choice questions. FF suggests a reason for her choice of answer in the question after Experiment 1. This question offers the conclusion that the tip and rhizoid must contain genetic material as these parts both developed a hat. FF refutes the alternative conclusion that the stem did not develop a hat because it was damaged when it was cut. Her argument is based on the idea that all the parts were dissected from the main cell, and the tip and rhizoid still developed:

... D'you reckon, cos like they'd all be damaged wouldn't they?

DM reasons about the evidence for the conclusion provided in the question following Experiment 2. The first statement provided in this question asserts that evidence from both Experiments 1 and 2 support the conclusion that a signal passes between the rhizoid and the tip so the stem is able to develop a hat:

Yeah I think it's the first one, yeah because it was a conclusion from the second experiment as well. The stem by itself wouldn't grow any more.

Data from Question 8 supports the idea that students are able to link evidence to simple conclusions. All but two of 47 students were able to write at least one conclusion from the Hammerling experiments backed up by evidence. The Centre A students also provided

examples of evidence from the experiments which refuted the conclusion (usually from one of the earlier experiments). LF uses conflicting evidence from Experiments 1 and 3 in Question 8:

Conclusion: All the genetic material is contained in the nucli

Supporting evidence: Experiment 3: the stem that contained the nucli form the rhizoid grew into a complete hat

Conflicting evidence: Experiment 1: some genetic material could be in the tip as the tip can develop a hat even when the nucli is cut off.

The post-interviews also provide examples of students' explanations, but these are at the level of simple inferences:

... the green hat grew cos there were still chemicals in the stem. [AM]

... grew its original flower, which shows that there is a bit of genetic material in the rhizoid [HF]

Although explanations backed up by evidence are not prompted in the pre- and post-tutorial test questions, evidence from students' written answers shows a difference between the pre- and post-tutorial responses.

In the pre-tutorial test carried out by the students from both centres, answers to the question about how the nucleus controls development drew on generalised ideas. The responses referred to genes having a code or producing proteins of a particular shape, for example. Of the 32/54 attempts to answer this question, 12 involved an explanation in terms of the genes affecting the structure of proteins, 16 were explanations in terms of genes containing information which affects cell processes, two explained the effects of genes in terms of inheritance and two were explanations in terms of the transcription and translation.

In the post-tutorial test, there were examples of responses which were in the format of evidence from a specific experiment plus explanation:

... For example, in plant cells the stem is only able to develop if the nucleus in the rhizoid is present. The genetic material is present in the rhizoid, so if there is no nucleus the shape of the hat may be different...

Ten of 37 responses in the post-tutorial test were constructed as evidence plus explanation in the context of *Acetabularia*, even though some of these answers had rather vague references to the Hammerling experiments.

The multiple choice questions in the tutorial provide conclusion statements, so students have to link the conclusions provided to evidence from the experiments (Figure 4.2). These questions require students to consider how data from several experiments might contribute to inferences about the control of development in *Acetabularia*.

The transcripts suggest that the complexity of the logic task in these questions can cause confusion as they support students to construct explanations supported by evidence:

... like its saying that Experiment 1 is saying it is incorrect, but then on the last one it says this is a valid conclusion from Experiment 2 only. So what does that mean really? [FF screen 14]

.... wha where? It looks like one big paragraph [DM trying to make sense of the three optional answers on screen 6]

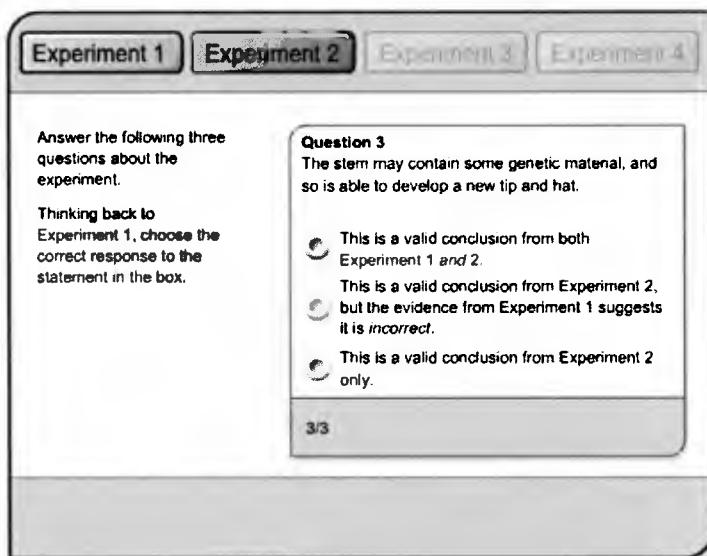
Figure 4.2 A multiple choice question after Experiment 2 in the tutorial (Screen 12)

The screenshot shows a user interface for a tutorial. At the top, there are four tabs labeled 'Experiment 1', 'Experiment 2', 'Experiment 3', and 'Experiment 4'. The 'Experiment 2' tab is currently selected. Below the tabs, there is a text box with the following instructions: 'Answer the following three questions about the experiment. Thinking back to Experiment 1, choose the correct response to the statement in the box.' To the right of this text box is a 'Question 1' box. The question text in the box is: 'When the rhizoid is left attached to the stem, some sort of signal passes up the stem to the tip from the rhizoid, so the stem becomes able to develop a hat.' Below the question text are three radio button options, each followed by a statement:

- This is a valid conclusion from both Experiment 1 and 2.
- This is a valid conclusion from Experiment 2, but the evidence from Experiment 1 suggests it is incorrect.
- This is a valid conclusion from Experiment 2 only.

 At the bottom of the 'Question 1' box, there is a small text area containing '1/3'.

Figure 4.3 Multiple choice question after Experiment 2 (Screen 14)



The evidence from FF and DF below suggests that immediacy of feedback which allows students to check the answer to the question by submitting a 'guess' presents a barrier to articulation of and reflection on their explanations. EF and DF submit two incorrect responses before getting the correct one on screen 14:

EF ... cell may contain. Yep top I think

DF Doh

EF We're not very good at this. Evidence from Experiment 2 might suggest. Well that's got to be that one hasn't it?

DF No. We're rubbish.

The inference from this data, and other similar examples, is that the feedback available through the interactivity of the multiple choice questions resulted in superficial consideration of the optional answers before clicking to elicit feedback. This misuse of the feedback represents a lost opportunity to scaffold articulation and reflection more carefully at these stages, designed as checkpoints in the tutorial. Students often reach a correct response to the multiple choice questions without much discussion of why they have selected a particular answer. This is illustrated by evidence of 'test-clicking' to discover the answer, reducing the amount of discussion.

... did we try that first one to see if that's wrong? [IF screen 14]

DF That one, isn't it?

EF Yeah

DF Yey [DF and EF do not discuss how they achieved the correct answer on screen 21]

IF right another question

FF Oh God I really don't know this time. This?

IF Maybe yeah. Don't know. [FF and IF submit a response to check if the answer is correct on screen 13]

There is evidence that the multiple choice questions do encourage students to discuss the problems in some cases. In the question on Screen 14 (Figure 4.3), students consider the evidence from the Hammerling experiments for where the genetic material is situated in *Acetabularia*. The exchange below shows how the question promotes discussion referring back to experiments 1 and 2. It focuses students' sense-making in a way that may not arise naturally following observations from these experiments. A possible theory to explain the results of Experiment 2 is suggested on this screen: 'the stem may contain genetic material and so is able to develop a tip and a hat'.

LF ... I thought the first one didn't work so in the second experiment did the tip grow a hat?

DM Yeah

LF then it could be the second one. [LF and DM screen 14]

Cos it grew a hat both times, didn't it? Oh no. Oh no actually I s'pose. Cos like in the first one there was like just the stem bit and it didn't grow anything, did it? [FF screen 14]

Students' discussion on Screen 14 (Figure 4.3) demonstrates how, with this particular question design, it is possible for students to discuss the question and to reach a 'correct answer' through logic, without requiring an explanation involving background science concepts and causal mechanisms.

Planning as an activity involving students in an inquiry

Although not part of the electronic tutorial, there are important design implications from the analysis of students' discussions as they carry out paper-based Question 6. To plan their own experiment using two species of *Acetabularia*, with the purpose of testing the idea that the nucleus controls development, students have to understand the entities they are manipulating and have ideas about the implications of their experimental manipulations. FF and IF review the earlier experiments to help them to decide what to do. The following extract shows how they reprocess their understanding of Experiment 1 before embarking on their own plan:

FF ... cos you know how they moved the nucleus to the stem and it could grow, could move it to that.

IF And you could have one with just the stem on its own

FF Yeah and then if you move it to the um the tip, you can see if it can grow like the you know forgotten what it's called the bit at the bottom

IF The rhizoid... [FF and IF transcript for Question 6]

This data shows that the requirement to produce their own plan leads students to suggest applications of their understanding of the earlier experiments. They justify their plans by suggesting what they expect to be revealed through further manipulations of *Acetabularia*.

These discussions suggest that students have predictive models for what will happen as a result of their planned interventions. Below, FF explains why the cell will develop into a mature *Acetabularia* on the basis of the model which predicts that the nucleus controls development:

... and this can grow into a full plant cos it's got like the nucleus and that, isn't it?

Students have to engage with the inquiry question as they plan their own experiment. LF realises she is not sure what they are meant to be testing:

... actually I don't know what we're meant to be testing to see um design an experiment to test the hypothesis. Well um the first experiment actually showed that...

Possibly as a result of having planned their own experiment, the reaction to the drag and drop animation of Experiment 4 shows much richer discussion than for the previous experiments.

DF and EF query the process in Experiment 4 as they watch the animation:

DF ... why's it chopping off?

EF To see what hat will grow there

DF That's ran-dom

EF No that's the right hat that's growing on

DF No I know but why did the first one grow the first time?

Similarly, FF and IF discuss the results, showing a wish to reach an explanation for Experiment 4 which was previously only prompted by the multiple choice questions following the experiments:

FF ... the new hat corresponds. Oh yeah cos just like this one's got that nucleus, it's just got a different stem

IF Well why did the other one grow?

FF That's just like the intermediate hat it's just like the first hat that grows is always the same for both or something like that ...

The evidence from this study shows that, by the end of the tutorial, students can make simple inferences from their observations and can back these up with appropriate evidence. They do not draw on background science to go beyond simple conclusions.

There is evidence that the multiple choice questions in the tutorial do encourage some discussion of the evidence for conclusions. They may also impose unhelpful cognitive load, through the complexity of the logic structure of the questions. Students may seek a quick result rather than struggling with difficult questions, and functionality that allows them to find the correct answer easily may discourage effort towards finding the correct solution. There is evidence that the multiple choice questions do not problematise the experiments in a way that encourages causal explanations of the observed phenomena.

The planning activity in Question 6 appears to prime students for a greater level of engagement as they watch the animations of Experiment 4 which follows. Experiment 4 shows how Hammerling carried out the experiment which the students were challenged to plan. There is also evidence that students approach the planning activity using predictive models based on their experience of the earlier experiments.

3. Interpreting scientific representations

The previous section on making observations in Science Inquiry Processes point 1 points to the evidence for students' ability to interpret specialised cell structures, such as the nucleus, in the new context of *Acetabularia*. Earlier sections also discussed the lack of evidence for links being made between development in *Acetabularia* and the relevant background science ideas about cells, DNA and development. This is the case even when students are prompted to make these links in the post-interviews. The evidence of confusion about what *Acetabularia* is suggests that students will not draw on relevant ideas from cell biology if the model which frames their reasoning is not *Acetabularia* as a single-celled organism. The significance of this confusion was discussed in the previous section in the context of constructing explanations.

As discussed earlier, the visual of *Acetabularia* looks like a small plant, and there is evidence that students interpret the cell parts as belonging to a multicellular organism. The data supporting this inference is set out in Section 4.2.2, Contextual ideas point 1. The labels associated with the visual include the term 'stem', which is likely to be familiar to students as part of a multicellular plant. Scaffolding needs to counteract the interpretations of the visuals based on students' greater familiarity with multicellular plants compared with single-celled algae.

Building on students' intuitive ideas is fundamental to successful learning in the domain of science inquiry, including background science ideas needed to make sense of the data. The post interviews show how students can be prompted to include ideas from prior learning that they would not otherwise use to explain phenomena. The following exchange between the interviewer and AM shows how the ideas from SNAB topic 2 are introduced. In particular, the word 'code' triggers topic 2 ideas about transcription and translation:

AM the stem won't create a hat without a nucleus.

Interviewer: Why do you think that is?

AM Because it's got. It doesn't have the genetic make-up in it.

Interviewer: Right, so where are the genes?

AM They're in the nucleus.

Interviewer: Right, and do you know anything about how the nucleus might be responsible for those chemicals. From your previous lessons?

AM Er. Nucleus might be responsible er.

Interviewer: What about. Do you remember back in topic 2 what do genes code for?

AM Oh they code for they are like tRNA and stuff like that

Interviewer: That's it yep

AM Code and that

Interviewer: That's it

AM Oh so it's tRNA the thing that gets attached to the ribosome, and then moves to the mRNA. Then amino acids come off that....."

The evidence in this section suggests that both visuals and technical terms used to describe the phenomena involved in an inquiry affect the way that students make sense of these entities. Previous learning can be built upon, as in the case of the nucleus being recognised as part of *Acetabularia*. Previous learning can also be a barrier if new phenomena are not presented in a way that draws on this knowledge usefully. For example, students' misinterpretations of what *Acetabularia* is are based on inappropriate prior learning cued by the words and visuals in the tutorial. Words and visuals need to be used effectively, so they prompt students to think in ways that are helpful for a particular problem.

4.3 Summary of students' learning

The initial analysis of evidence for learning and barriers to learning set out in this chapter was carried out with reference to the task model underpinning the tutorial (see Section 3.2). There is evidence showing that, by the end of the tutorial, in the context of the Hammerling experiments, most students know that the nucleus contains the cell's genetic material, the nucleus controls development of the hat and other parts in *Acetabularia*, and chemical signals communicate between the nucleus and cytoplasm. Students use and apply the names of the specialised parts of *Acetabularia*, and the techniques and processes used in the Hammerling experiments.

Confusion about what *Acetabularia* is persists throughout the tutorial. Possibly as a result of this, barriers to learning are evident around further confusion between the nucleus, genetic material and the chemicals in the cytoplasm. Students do not make the link between these chemicals and the processes of transcription and translation learned in the previous topic even when prompted to explain the causal mechanisms of development in *Acetabularia*.

Data from students carrying out the tutorial suggests that students need to make links with ideas from prior learning which relate to understanding that *Acetabularia* is a single cell. The analysis of prior learning from the pre-tutorial tests suggests that background science ideas from previous topics are not robust. The prior learning that should be available from previous topics, and which could contribute to explanations of development in *Acetabularia* includes:

- Knowledge of basic cell structure.
- Knowledge that genes are in the nucleus of a cell.
- Understanding that genes are responsible for proteins produced in a cell (through transcription and translation).
- Understanding that proteins in the cytoplasm control cell processes, including development.

Where the data shows these topics are fragile, scaffolding needs to support links to these ideas explicitly.

Science inquiry skills demonstrated as students carry out the tutorial include the ability to make observations and use evidence to construct simple explanations. Students show evidence of being able to follow the logical reasoning needed to make deductions from a scientific experiment. Barriers to producing causal explanations of development in *Acetabularia* appear to be linked to background science knowledge rather than inability to follow specific inquiry processes. Students recognise familiar cell structures in the representation of *Acetabularia*, but appear to misinterpret the visual as a multicellular plant. It is possible that the visuals and scientific terms used in the tutorial miscue ideas about what *Acetabularia* is, leading to problems with explaining observations from the experiments.

Certain features of the tutorial, including the multiple choice questions and visuals, are shown to stimulate articulation and reflection about the inquiry. There is also evidence that these same features can present a barrier to learning. The multiple choice questions add unhelpful complexity through their structure, and make discovering the correct answer too easy. This leads to students guessing the answer rather than spending time to reach a more considered response (see Appendix 8, Point 2. Constructing explanations):

DF ... I think it's that one

<indicating B>

EF Yeah

<incorrect message>

DF Doh

EF Maybe it's the bottom one

<submits C incorrect message>

DF Nope (laughs) we're not very good at this

<submits A correct message> [DF and EF guess the responses on screen 13]

In the next stage of this study, data is used to test the Quintana *et al.* (2004) framework. Rather than carrying out this next stage using all the categorisations of data from the initial analysis in this chapter, the scope of this study was reduced to a narrower focus. The focus selected for the next stage of analysis is the obstacle to learning suggested by confusion over what *Acetabularia* is. This is discussed in the next chapter, along with the implications of this confusion for building explanations and overarching principles about cells and development. The particular barrier to learning was chosen for focus because it exemplifies an important generalisable learning issue: how students' understanding of background science ideas can be supported through science inquiry.

Learning background science concepts is a crucial role of science inquiry in school practical lessons (Abrahams and Millar, 2008). This aspect of learning through inquiry is also important because, if students fail to recruit the appropriate background science ideas, or these concepts are confused, this will present a barrier to developing inferences and explanations from the data.

The analysis continues in Chapter 5 to test whether the generalised guidance provided in Quintana *et al.*'s (2004) framework fits the specific example of the *Acetabularia* tutorial. If the framework is sufficiently comprehensive, it should provide insight into the barriers to learning identified in the transcripts, and the scaffolding needs of students as they engage with the tutorial. Chapter 6 then provides some ideas for revisions to the tutorial in light of the data from this study, and for the implementation of the guidelines in revisions to the tutorial.

Chapter 5 The utility of the scaffolding design framework

5.1 A summary of the study so far

5.1.1 Findings from the data

Chapter 4 demonstrated that the student data collected in this study was rich in evidence of learning and barriers to learning associated with the *Acetabularia* tutorial. This initial analysis led to a decision to limit the scope of the next stage of the study by focussing on a specific area of science inquiry. Evidence from the data suggested the need for more effective scaffolding of background science as students develop explanations. This led to a focus on developing explanations in the next stage of the study.

Inquiry in science education often takes place as practical work which aims to teach substantial background science ideas in addition to inquiry processes (Abrahams and Millar, 2008). Fundamental to sense-making in a scientific inquiry is being able to position the inquiry within the bigger picture of a science topic or problem. To do this, students must make links between the domain of observables from an experiment and the domain of ideas which explain the observables (Tiberghien, 2000).

The *Acetabularia* tutorial aims to teach process skills associated with linking evidence and explanations in addition to background science about how the nucleus controls development. A barrier to learning evidenced in the data is associated with making sense of the observations from the Hammerling experiments. This could be described as a failure to position the inquiry in the context of a specific scientific model: control of development by the nucleus.

The data suggested that, due to confusion over the main protagonist in the story of science being set out in the tutorial, students fail to position the Hammerling experiments within the relevant background science topic. By not appreciating that *Acetabularia* is a single cell, students do not recruit the science from cell biology, genetics and development needed to make links with their prior learning.

5.1.2 The focus of this study

The Quintana *et al.* (2004) framework offers generalised guidance for inquiry processes. It is left to the designer to apply the guidance to the context of the inquiry they are scaffolding. This approach implies that it is possible to separate inquiry processes from background science content when generalised guidance is developed. The task model for the tutorial developed in Chapter 3 decomposes the categories of background science, contextual science concepts and inquiry processes. In the enactment of an inquiry, the inquiry processes and background science content are essential and integrated elements of scientific sense-making.

The specific inquiry task that is identified as problematic from the data in this study is developing explanations at the level of causal mechanisms, by integrating science concepts and empirical evidence. The need to integrate knowledge of background science with processes as explanations are constructed is not articulated in Quintana *et al.*'s (2004) framework. The tension between generalised guidelines and their application in specific contexts was discussed in Chapter 1. In this chapter the data is used to challenge the utility of the generalised scaffolding design strategies in the framework.

5.2 Revisions to the task model for the next stage

The analysis of the data against the task model for the tutorial leads to the conclusion that the separation of background science, contextual science ideas and science inquiry processes is a sophisticated and expert view of the learning involved in science inquiry. This task decomposition underpinning the task model does not necessarily reflect students' perceptions of the learning tasks.

The separation of background science and contextual science ideas stems from the view that knowledge of general, overarching scientific principles can be exemplified in many different contexts during learning, but that this must contribute to students' perception of the generalised scientific concepts. *Acetabularia* is a specific example of a cell. Development in *Acetabularia* is a specific example of development in a single cell. The idea is that students generalise from such specific examples to broaden and deepen their understanding of cells and development.

The contextual story of the Hammerling experiments also exemplifies the application of scientific inquiry processes in a specific situation. Scientific inquiry processes are generalised in the third category of the task model for the tutorial.

The challenge of using science inquiry learning to develop explanations involving accepted scientific theories is evidenced in the data from this study. The data suggests that there is a barrier to students drawing on scientific theories from prior learning which explain Hammerling's observations. Confusion over what *Acetabularia* is may contribute to this difficulty. This inference from the data also exemplifies the interconnectedness of scientific theories and scientific inquiry processes. It is not possible for students to make sense of an inquiry without access to explanatory scientific theories.

If it is the case that scientific explanations involve processing new contextual ideas in the light of generalised theories, keeping the three categories of the original task model separate may not arrive at a useful critique of the framework. The question of whether the framework provides sufficient guidance for design of scaffolding to support development of explanations needs to be considered with reference to what this task really involves for learners. For this reason, the task model was reorganised to reflect more clearly the cognitive tasks which the data suggest are involved in students' learning.

Students need to interpret the findings from the Hammerling experiments in the light of understanding that *Acetabularia* is a single cell. The data shows that, if they don't, they may not draw on relevant scientific concepts to explain the experiments. The inference from this finding is that establishing *Acetabularia* as a single cell should precede reasoning about the experiments. The data also suggests that more effective scaffolding is needed to help students to draw on their relevant prior learning. For example, students need to make the link between development in *Acetabularia* and protein synthesis from the previous topic. In turn, the conclusions from the Hammerling experiments should refine students' understanding of the role of the nucleus in cells more generally.

Table 5.1 structures the existing task model categories of background science, contextual science and science inquiry processes against the narrative of the *Acetabularia* tutorial. The new model uses the analysis of the data to suggest how the elements of content from the original task model fit into students' learning journey. The barrier to drawing on prior learning was identified from the data, so the new arrangement of the task model includes prior learning to

show where it is needed to support sense-making. The categories of relevant prior learning reflect the summary at the end of Chapter 4 (Section 4.3) where the previous SNAB topics necessary for explaining development in *Acetabularia* were listed.

This narrative approach to the task model suggests a scenario for how knowledge and understanding might develop through the tutorial, drawing on prior learning. The new model identifies the following main stages:

- 1) Establishing the entities involved in a specific inquiry.
- 2) Using the methods of scientific inquiry and reasoning to manipulate the entities, to collect data and to make inferences from the data.
- 3) Use scientific models to explain the inferences from the data.

The entities referred to in stage 1 include the unfamiliar protagonist in the story, *Acetabularia*, and more familiar entities from prior learning, such as cells, cell structures and protein synthesis.

The data analysis against the task model in the previous chapter suggested that students are able to follow the logic of a scientific inquiry, and can produce conclusions backed up by evidence. The analysis also suggests that stage 3 should be included in the task model, based on the evidence that students' learning remains isolated in the context of the tutorial if links are not explicitly made with generalised background theories.

These three stages, involving the rearrangement of the elements in the original task model, and showing the relevant prior learning which needs to be involved if students are go beyond simple inferences from the data, form the categories for testing the Quintana *et al.* (2004) framework in the next stage of this study.

Table 5.1 The narrative of an inquiry leading to the explanation for development in *Acetabularia*

Narrative from the tutorial	Relevant prior learning	Background science	Contextual science	Science inquiry processes
Cells are the basic unit of life. As a unicellular organism, <i>Acetabularia</i> is a specific example of a cell with specialised structures.	Knowledge of basic cell structure.	1. Cells contain specialised structures.	1. <i>Acetabularia</i> is a single cell with specialised parts (hat, stem and rhizoid).	3. Interpreting scientific representations.
Acetabularia is large enough that it can be manipulated to investigate which part of the cell controls development.		2. Acetabularia is ideal for this type of inquiry, because it is large enough to dissect and manipulate.	2. Acetabularia is ideal for this type of inquiry, because it is large enough to dissect and manipulate.	
Scientific inquiry processes lead to the deduction that chemicals produced by the nucleus move into the cytoplasm and control development of the hat in <i>Acetabularia</i> .			3. A complete cell develops from any cell part that has the nucleus present, or from parts to which the rhizoid containing the nucleus has remained attached after removal of the hat.	Analyzing data (observations). Constructing explanations.
This is a specific example of the role of the nucleus in all cells. It can be explained using theories about how the nucleus controls which proteins		4. A chemical signal travels between the nucleus and the cytoplasm, and these chemicals in the cytoplasm determine development of the cell parts.	2. The nucleus contains the cell's genetic material.	2. Constructing explanations.
		Genes are in the nucleus of a cell.	Genes are	135

are produced in cells.	<p>responsible for proteins produced in a cell (through transcription and translation).</p> <p>Proteins in the cytoplasm control cell processes, including development.</p> <p>3. The genetic material contains the code which controls which proteins (and other chemicals) are made in the cytoplasm.</p> <p>4. Chemicals in the cytoplasm control the cell's activities (which chemical reactions take place).</p> <p>5. Development of characteristics (including specialised structures in the cell) is controlled by chemicals in the cytoplasm.</p>
------------------------	--

5.3 Establishing the entities involved in a specific inquiry

The organisation of the task model suggested in Table 5.1 includes the elements of the original task model and prior learning in the categorisation of establishing the entities shown in Table 5.2.

Table 5.2 Task model elements involved in establishing the entities

<i>Narrative</i>	<i>Relevant prior learning</i>	<i>Background science</i>	<i>Contextual science</i>	<i>Science inquiry processes</i>
Cells are the basic unit of life. As a unicellular organism, <i>Acetabularia</i> is a specific example of a cell with specialised structures.	Knowledge of basic cell structure.	I. Cells contain specialised structures.	I. <i>Acetabularia</i> is a single cell with specialised parts (hat, stem and rhizoid).	3. Interpreting scientific representations.

The data shows there is confusion over what *Acetabularia* is. One possible inference from this study is that fragile background science results in a barrier to students making links with relevant prior learning needed to make sense of the Hammerling experiments (Section 4.2.2).

If the tutorial is considered as part of a holistic teaching sequence, post-tutorial evidence showing that students do not make sense of the Hammerling experiments using relevant background science can't be brushed aside with the argument that the tutorial did not set out to do this, even if students successfully complete the tasks in the tutorial. This study represents an opportunity to explore how background science can be scaffolded during inquiry.

An implication from the data is that 'knowing' the background science ideas which constitute explanations is not sufficient for students to be able to construct an explanatory narrative for unfamiliar observed phenomena. Some students were able to describe transcription and translation in the pre-tutorial test (Section 4.1) but only used this as an

explanatory idea for control of the nucleus when explicitly prompted to do so in the post-tutorial interviews. Other students showed they could not automatically resituate this prior learning to explain a new context, or that their interpretation of the data involved misconceptions:

... that was basically showing that the tip had some of the um like DNA able to produce a hat. [FF explaining Experiment 1 in the post-tutorial interview]

The design of the SNAB course assumes that new knowledge builds upon prior knowledge in a spiral curriculum (Bruner, 1974). Finding evidence in this study that students do not make these links with prior learning, or with the wider story of the topic, justifies the focus in this chapter on how the background science can be better scaffolded in an inquiry.

The next sections discuss the importance of background science ideas as students make sense of an inquiry, and how the inquiry supports construction of increasingly complex and overarching science explanations.

5.3.1 Establishing *Acetabularia* as an ontological entity

Acetabularia can be envisaged as a concept which has to be understood. It has an explanation in the same way that 'development' is an explanation for *Acetabularia* growing a hat. Constituent ideas nest within this ontological entity (Vygotsky, 1987; Ogborn et al., 1996) of *Acetabularia*. The ideas of individual cell organelles, the nucleus, genes and cytoplasm all nest within the concept '*Acetabularia*'.

The significance of students' confusion over what *Acetabularia* is can be interpreted using the idea that understanding science is about developing and managing the taxonomy of nested explanations (Ogborn et al., 1996). This view of sense making emphasises the importance of establishing the individual entities which constitute explanations in an inquiry. These include the individual entities which act in an inquiry and their constituent, nested entities, through to the level of overarching scientific principles. If schemas for the individual entities are not robust, they will not successfully form building blocks for overarching principles.

The *Acetabularia* tutorial could be considered a complete, stand alone activity, finishing as it does with students drawing simple inferences from the experiments, rather than leading to explanatory mechanisms of development. Students' responses in Question 8 suggest that the tutorial has some success in this outcome (Section 4.2.3). But the post-tutorial data suggests that students do not see development in *Acetabularia* as a specific example of the

wider concept of development nor appreciate the link to protein synthesis. Neither do they see it as an example of specialisation in a single-celled organism. If they did, the relevant background science ideas might be accessed more consistently to explain the outcomes of Hammerling experiments. The evidence for interpretations based on misconceptions of background science also suggests that explanations should be more carefully introduced in the tutorial.

Scaffolding to promote links with prior learning is not straightforward; even when prompted to think about what they learnt in SNAB Topic 2 in the post-tutorial interviews, students had difficulty relating ideas about transcription and translation to this new context (Section 4.2.3). New knowledge from the tutorial will not be available for future problem-solving if the entities constructed in the tutorial are not positioned explicitly within a framework of broader principles of biology. For example, if students do not understand that *Acetabularia* is a cell, the Hammerling experiments will not reinforce the nesting of the explanation of transcription and translation within cell development. Nor will the *Acetabularia* tutorial contribute to the more overarching concept of development, and students' understanding of cells will not be broadened to include single-celled organisms.

Constructivist theories of learning suggest that knowledge is organised into mental structures called 'schemas', which are then refined as new knowledge is introduced (Anderson *et al.*, 1977). Students should build increasingly complex schemas as the science concepts that they understand are exemplified and applied through inquiries and problems set in a range of different contexts. If students' explanations of new phenomena do not make links with relevant background science from previous topics, new learning will remain isolated.

Situated learning theorists describe this process as learning to talk as an 'increasingly less peripheral participant in a shared practice' (Lave and Wenger, 1991, p. 109). Science inquiry aims to induct students into the shared practices of science. The efficacy of the tutorial can be judged by whether it scaffolds this process of resituating knowledge through the stages of the Hammerling inquiry, allowing students to participate in the talk about development in the context of *Acetabularia*. In the longer term, its success would need to be judged through students' application of new knowledge and understanding to wider contexts.

Students need to understand what *Acetabularia* is to understand the context of Hammerling's inquiry. The inquiry is not to find out what *Acetabularia* is, it is to discover what it does, and to make inferences about the control of development from how

Acetabularia behaves in the experiments. Understanding of what *Acetabularia* is becomes meaningful through making links with what it does. For example, when *Acetabularia* grows a hat this alerts students to the idea that *Acetabularia* has specialised parts with specific functions. What *Acetabularia* 'does' in the experiments affects how students 'see' the nucleus in *Acetabularia*. The nucleus embodies a new meaning, as a structure with a controlling role, determining which hat develops. This resonates with Ogborn's discussion of the educational purpose of scientific inquiry in school science, as leading students to a particular way of 'seeing' (Ogborn et al., 1996, p. 130).

The pre-tutorial tests provided evidence that students are confused about basic background science ideas which are fundamental to understanding how the nucleus controls development in *Acetabularia*. For example, some students were confused between proteins and DNA, and many could not explain how genes control processes in cells (Section 4.2.1). This is an argument for establishing these entities at the start of the tutorial, in addition to establishing new entities such as *Acetabularia*. The aim would be to support fragile understanding from prior learning so this does not present a barrier to learning more about genes and development from the new situation of development in *Acetabularia*.

There is evidence from this study that students develop some knowledge of entities which are presented in the context of the inquiry and which serve as tools for explaining development in *Acetabularia*. By the end of the tutorial, students can explain what development means for *Acetabularia*, at the level of 'the tip develops a hat' or 'the rhizoid develops into a whole cell'. They can also explain development in terms of control from the nucleus: they know that the nucleus is needed for development to occur (see data under *Constructing explanations*, p.120).

There is, though, little evidence that students make the connection between the chemical signals which convey information from the nucleus to the tip of *Acetabularia* and prior learning about DNA or transcription and translation (producing proteins in the cytoplasm). The data shows students are confused about the distinction between the nucleus, genetic material and the chemicals in the cytoplasm, while being aware that these are involved in development of specialised parts of *Acetabularia* (see data on Background Science Point 5. p. 110).

The Quintana et al. (2004) framework's Guideline 1 suggests using visuals and language to 'bridge learners' understanding'. This guideline implies scaffolding which supports resituating of science topics by 'bridging' between the old and the new context. However, the

framework does not explicitly guide the design of scaffolding to make links with background science learning. There is an assumption in the framework's guidance that students' prior knowledge of the entities which act in an inquiry can be resituated as long as scaffolding sufficiently guides inquiry processes.

The data from this study questions this assumption, suggesting that establishing the key entities represents a scaffolding need in inquiry. For example, an inquiry into the properties of amylase will not help students solve future problems involving enzymes unless they understand both that amylase is an enzyme and what an enzyme is. Students need to position amylase within the broader concept of enzymes if they are to resituate this knowledge in later problems. The *Acetabularia* tutorial will not contribute to students' broader conception of cells and development if they do not understand that *Acetabularia* is a cell. Nor will they explain the observed phenomena in terms of cell biology if this is the case.

Chapter 2 highlighted the tension between treating inquiry processes and science concepts separately. Layton (1973) argues that these elements can't be processed simultaneously and Millar (2004) argues that processes do not make sense without the context of the scientific theories. The original task model set out in Chapter 3 showed how these elements can be separated in the decomposition of the tutorial, but the re-categorisation of the tasks and prior learning in this chapter moves to a more integrated description of the cognitive tasks (Table 5.1 p.135). The constituents of scientific sense making may need to be considered separately by designers of scaffolding for inquiry, so each is given sufficient attention. But, the data suggest scaffolding is needed to support students as they integrate these elements, so they make sense of an inquiry using their knowledge of background science. This contrasts with the emphasis in the Quintana *et al.* (2004) framework which does not consider how inquiry processes are integrated with background science.

This study concludes that background science should be scaffolded according to a task model which includes the nested entities which need to be understood and relevant prior learning that needs to be recruited. The following section uses data from this study to comment further on the level of guidance for designers in the Quintana *et al.* (*ibid*) framework in the area of scaffolding background science ideas.

5.3.2 Testing Quintana et al.'s Guideline I to support the establishing of entities

Using visuals that link with students' prior learning

Previous sections discussed how students need to understand what *Acetabularia* is, as the protagonist in the story of science being unfolded in the tutorial (Ogborn et al., 1996). Students also need to know what *Acetabularia* is so they make links with relevant prior learning of the background science associated with cells and cell biology. The tutorial uses both visuals and language in communicating the background science. The evidence from this study for the need to establish *Acetabularia* as an entity fits with Guideline I of the Quintana et al. framework:

Guideline I: Use representations and language that bridge learners' understanding.

(Quintana et al., 2004, p. 348)

Guideline I refers to the importance of using intuitive language and representations. The strategies under this guideline address a barrier to learning where students lack domain-specific expertise needed to guide the sense-making process and to work with formalisms of the discipline. Ways of presenting domain specific content, including specialised vocabulary, present a barrier if they do not connect with students' prior learning (Quintana et al., 2004).

The following utterance:

... this is a cell, isn't it? [LF screen I]

along with other similar examples of students referring to *Acetabularia* as a cell, shows a fit with scaffolding strategy 1b in particular:

Strategy 1b: Use descriptions of complex concepts that build on learners' intuitive ideas.

(Quintana et al., 2004, p. 348)

The visuals and text on Screen I (Figure 5.1) bridge between LF's prior learning about cells and the *Acetabularia* cell of the new context. The data provided other examples where students recognise familiar structures such as the nucleus, allowing them to recognise these as part of the *Acetabularia* cell (see data in Appendix 7 point 1). The inference from this data is that aspects of strategy 1b are exemplified by features of the visuals used in the tutorial.

Other examples of data provide evidence of confusion about what *Acetabularia* is. The following entry is categorised in the data analysis as a barrier to establishing *Acetabularia* as a cell:

... so is this the same plant we're doing? [DM screen 7]

At this point, DM is looking at a photograph of *Acetabularia* on the experiment selection screen, and appears not to make the connection between the photograph and the visuals of *Acetabularia* in the tutorial's task screens. Furthermore, he refers to *Acetabularia* as a 'plant'. In this case Scaffolding Strategy 1b suggests how this barrier to learning could be avoided through more effective scaffolding. Scaffolding must support students to make the link between diagrams and photographs used and between *Acetabularia* and prior learning about cells.

Currently, the bridging with learners' intuitive ideas is only exemplified and discussed in the Quintana et al. (*ibid*) framework with reference to inquiry processes. The data from this study suggests that scaffolding is also needed for background science ideas. The existing scaffolding design strategies could be applied to this content and scaffolding for building on students' intuitive background science understanding could be exemplified in the framework.

In the framework visuals are described as scaffolding tools in terms of representations which 'bridge understanding' in Guideline 1 and representations which 'reveal important properties of underlying data' in Guideline 3 (Quintana et al., 2004, p. 345). Both these guidelines acknowledge the task of interpreting representations in terms of identifying patterns in data through visual organisers. As such, the guidance refers to inquiry processes rather than background science.

Guideline 1 in the framework describes *WorldWatcher* software (Edelson, Gordin and Pea, 1999) which uses an energy balance diagram to structure investigations of atmospheric data. *Astronomy Village* (Dimitrov, McGee and Howard, 2002), in the same section of the framework, uses visual scenes from laboratories to organise access to selected data.

Guideline 1 does not comment on the design of visuals used in these software tools, nor discuss the importance of visual models in conveying coded information on background science concepts. This is an omission, because even visual organisers which provide access to data are constructed around visual models which represent scientific entities or ideas. It should not be assumed that the type of interactive diagrams used in *WorldWatcher* and

Astronomy Village software will communicate the ideas that the designer intended, or that the visuals which make up the organisers will not introduce misconceptions.

Ainsworth (2006) points out that the affordances of visuals in learning resources depend on a complex interaction between the design parameters of the visuals. The parameters include why a particular type of representation is chosen, the representational function of the visual in terms of the information which it encodes, and the cognitive tasks which learners engage with when using the visuals. Visuals shape how a task is perceived and are central to scientific reasoning (Norman, 1991). If there is a gap between representations of phenomena and the way students intuitively think about them, then the task of noticing what is important about scientific situations may not be supported.

The visuals of *Acetabularia* in the tutorial are models, that is simplified representations of particular aspects of phenomena (Gilbert, Boulter and Rutherford, 2000). In particular, the visuals aim to highlight features of the *Acetabularia* cell which are relevant to the inquiry (hat, nucleus, stem and rhizoid).

In the *Acetabularia* visuals, the nucleus is communicated using a solid black dot, and this is how nuclei are generally shown in low magnification diagrams of cells in biology textbooks. The parts of *Acetabularia* shown in the visuals in the tutorial are selected as those which are relevant to the explanation of development in the cell. Other parts are omitted. The diagram is uncluttered with irrelevant structures such as chloroplasts, vacuoles or reproductive cysts. Bridging understanding as Quintana et al.'s (2004) strategy 1b suggests is about positive use of signs and formalisms which students can interpret. It also involves selecting certain signs and representations to bring to the fore, while selecting others to background. Focussing students' attention on the salient ideas during sense making is an important role of visual representations.

The design decisions made in selecting these representations apply to the type of visual organisers described in the Quintana et al. (*ibid*) framework, as well as visuals models and representations of actual structures. Scaffolding strategy 1b could usefully be illustrated with this additional dimension, where visual literacy is seen as important in providing descriptions of complex concepts that build on learners' intuitive ideas.

The guidance in the framework suggests that the design of visuals should build on representations that students have become familiar with previously. The ontological understanding of the physical entity of *Acetabularia* and its constituent structures must be

linked with previous experience of the 'black dot' structure in cell diagrams. The black dot nests ideas of the nucleus as the store of genetic material which controls development.

The pre-test data in this study provide evidence that students have schema relating to the nucleus before they start the tutorial. They then recognise the nucleus in an unfamiliar context in the tutorial, which allows them to learn from manipulables showing what happens when the nucleus is transferred into other cell parts. Quintana *et al.* suggest that this strategy is commonly used in learning resources, where grounding learners' understanding by helping them to access familiar ideas allows them to build more complex and formal concepts (Quintana *et al.*, 2004).

Interpreting representations is listed in the *Acetabularia* tutorial's task model as an inquiry task. This reflects the observation from the student data that the visuals do not always cue the appropriate information about what *Acetabularia* is. Any miscuing of information about *Acetabularia* through the visuals will contribute to students' confusion about what the organism is. Failure to acknowledge the challenge of interpreting visual models and representations used in software is identified here as a gap in the Quintana *et al.* (2004) framework.

A recommendation from this study is that a strategy should be added to address this gap in the framework. Sutton (1992), in his discussion of language in science teaching, suggests that teachers should spend time talking about words and their meaning, so students can enter into the systems of speech and thought of the discipline. In a similar way, scaffolding should stimulate discussion which encourages greater appreciation of the conventions used in formal scientific visuals.

For example, a new strategy might be 'Provide expert guidance on the conventions of visual representations and models'. This strategy complements strategy 1b by referring to visual literacy and the status of models. Strategy 1b refers to choosing models or representations which build on students' intuitive understanding.

Visual literacy guidelines for science inquiry learning

Scaffolding strategies following the new strategy might emphasise the role of making scale explicit in the diagrams of *Acetabularia*, or might provide guidance on interpreting 2-dimensional sections in biological diagrams.

In the design of the drag and drop manipulables and animations in the tutorial, the focus was on communicating what *Acetabularia* 'does' as a result of experimental manipulations rather than what it 'is'. The data suggests that interpreting what *Acetabularia* does was difficult where students were confused about what it is. For example, some students discussed development as if the nucleus were controlling specialisation in a multicellular plant:

A gene may be included into the nucleus which would send out chemical signals to different cells influencing the development of a remote part. For example, in a plant the stem may produce a new head/ hat ... [from Centre B post-tutorial test]

This emphasises the point that the framework needs to provide strategies for emphasising the appropriate visual cues about entities in addition to using the visuals as a vehicle for embedded data.

Interpreting Guideline 1 in relation to background science ideas would lead to visuals of *Acetabularia* which draw on students' existing mental models of cells and cell parts. The visuals should bridge students' ontological understanding of the physical entity of *Acetabularia* and its constituent structures. The importance of recognising the representation of the nucleus lies in the links this establishes with the range of ontological ideas which students associate with the nucleus. These include properties of the nucleus and how it acts in its environment. For example, it is the store of genetic material which controls development. Representations of the nucleus also signal ideas about its relationship with other entities: it is a cell organelle, which is within a cell. The entity of 'nucleus' nests within the entity 'cell', as discussed in Section 5.3.1.

The data suggests that what actually happens as students interpret the visuals in the tutorial, is a confusion between 'cell', cued by the nucleus and 'plant' cued by the stem and hat of *Acetabularia*. The stem and hat appear to trigger ideas about the stem and flower of a multicellular plant (see data Section 4.2.2).

This section concludes that visuals have an important role in establishing the ontological entities which act in an inquiry. This is an argument for more explicit guidance within Guideline 1 on designing visuals which effectively cue the appropriate background science ideas from prior learning and for providing guidance which helps students to interpret visuals. These points apply to visuals used in visual organisers in addition to the visuals designed primarily to communicate background science ideas.

Using language that links with students' prior learning

Language in science has parallel affordances to the visual representations discussed in the last section: both are for creating and communicating ideas. Learning new terms is part of a learners' apprenticeship in science as is learning about the conventions of scientific representations. Scientific terms help scientists to communicate shared understanding, so students will be excluded from the world of scientific explanations if they are not supported to develop their own scientific vocabulary. Learning to use the terminology of the discipline also gives students access to the culture of science, including scientific reports and media discussions about scientific issues.

Section 2.5.3 discussed the role of words in guiding the way students think about phenomena. The data from this study shows that, by the time they carry out the written Question 6, students link the terms, hat, stem, nucleus and rhizoid with their associated structures in *Acetabularia* (see data Section 4.2.2, point 1).

But the data also shows that confusion about what *Acetabularia* is has been introduced by the information provided in the tutorial. The scaffolding solutions exemplified in the software described under Strategy 1b in the Quintana *et al.* (2004) framework 'Use descriptions of complex concepts that build on learners' intuitive ideas' suggest designers should avoid using unfamiliar technical terms to represent ideas. For example, the Cybertracker software (Parr, Jones and Songer, 2002) is used as an example of how intuitive terms can replace technical schemes for classifying animals. This conflicts with Vygotsky's (1978) idea that students need to learn the language which embodies concepts in science. It is important that technical words are introduced, certainly by advanced level study, as they are involved in transformation of thought (Sutton, 1992). Scaffolding must bridge the gap between learners' intuitive ideas and new technical terms.

From a design point of view, it is important to distinguish between technical 'labels' and technical terms which embody more complex ideas. In the former case, a decision needs to be made about the appropriateness of introducing a technical term where a more familiar term is sufficient. For example, as the evidence shows that terms such as 'rhizoid' distracts students from discussing the main ideas in the tutorial, 'rhizoid' could be replaced in the *Acetabularia* tutorial with a less problematic term such as 'base' (see data Section 4.2.2, point 1. *Acetabularia* is a single cell with specialised parts).

Technical terms which embody complex ideas should build on the conceptual foundations of these ideas and students' intuitive ideas as suggested in Guideline 1. Words steer

perception in science, leading students to new ways of seeing the world. These new ideas will not be created simply by introducing the technical terms which communicate them (Sutton, 1992). Decisions about the use of terms is far from straightforward, as words which could superficially be categorised as labels actually embody crucial ideas in a particular context. The word 'cell' is an example of this in the *Acetabularia* tutorial. It is not just a way of labelling the structure, but it brings with it all the nested knowledge about cell biology which is needed to interpret what *Acetabularia* is and the events in the Hammerling experiments. This is in contrast to labels for ideas which are not crucial for students' understanding. It is not necessary for students to understand what the hat, stem and rhizoid are in *Acetabularia*, beyond being specialised structures of a cell.

Text to describe facts and give information about *Acetabularia* is shown on Screen 1 (Figure 5.1). Familiar labels such as 'cytoplasm' and 'nucleus' should excite connections with the concept of cells. These types of labels used for scientific formalisms have a precise, agreed meaning which embodies a specific idea (Sutton, 1992).

Figure 5.1 Screen 1 introduces *Acetabularia*

Acetabularia

Acetabularia is a green alga consisting of a single cell, 2–3 cm long. It has a rhizoid at one end, containing the nucleus, and a 'hat' at the other end.

Because it is such a large cell, it is possible to perform microsurgery on it, dissecting up the sections, and transferring the nucleus from one section to another. It has been used to study the role of the nucleus and cytoplasm in development.

Page 1 of 2

Next

The diagram illustrates the structure of *Acetabularia* as a single, elongated cell. At the top (the 'hat' end), there is a circular, radiating structure representing the cytoplasm. Below this is the 'stem', which is a narrow, vertical tube. At the very bottom (the 'rhizoid' end), there is a small, root-like structure. A horizontal line extends from the middle of the stem to the right, with a bracket and the label 'nucleus' pointing to the point where the stem meets the rhizoid. Another horizontal line extends from the top of the stem to the right, with a bracket and the label 'hat' pointing to the top cap. A third horizontal line extends from the bottom of the stem to the right, with a bracket and the label 'rhizoid' pointing to the bottom structure.

Confusion arises when analogies such as 'hat' are used as descriptive terms in science, as these bring alternative meanings (Sutton, 1992). 'Stem' is used as a label for the extended cytoplasm joining the rhizoid and hat in *Acetabularia*, using the analogy of stems in

multicellular plants. 'Stem' may, though, cue the idea that *Acetabularia* is a multicellular plant, and could be a source of pedagogic error⁸.

The familiar term 'hat' is an analogy for the reproductive structure on the top of *Acetabularia*. The label 'hat' requires students to reinterpret the word in this new context. 'Rhizoid', as an unfamiliar term, does not bring associated meanings, and provides a precise label for this part of *Acetabularia*. The new term is processed as students apply the idea it represents when completing the tasks of the tutorial.

A conclusion from the data is that where learning resources use language with narrowly denoted definitions agreed by the scientific community, it should not be assumed that students do not associate alternative meanings with these terms. Words such as 'rhizoid' can stand for technical ideas without unhelpful associations, although, as discussed earlier, depending on the age and experience of the learner, it may be preferable to replace such terms with more straightforward labels such as a 'base'. On the other hand, this type of everyday term, including 'hat' and 'stem', require students to go against their intuitive understanding of the language.

'Development' is another example of a word which has different meanings in different contexts. Even in the narrow biological definition of an organism changing over time, the meaning of development as it applies to whole organisms does not exactly transfer to development in a single cell. Development in multicellular organisms refers to specialisation of cells into tissues and organs. This was the context of learning about development in SNAB Topic 2. In Topic 3, 'development' in *Acetabularia* refers to specialisation of structures within a single cell. There may be a similar problem with the word 'dissection' used with reference to *Acetabularia*, as this term is more familiar in association with multicellular organisms.

Changes of context do not automatically result in switching from one meaning of a particular word to another. As words are intrinsic to context, and are linked with the other words that contribute to that context, communication of meaning relies on building up enough connections within and between contexts for learners to appreciate what the word represents in different situations (Hayakawa and Hayakawa, 1990). Supporting learners as

⁸ Pedagogic errors are equivalent to iatrogenic diseases, caused by doctor's actions (Laurillard, 2002). In this case they are errors in understanding caused by the teacher or tool.

they experience these shifts in meaning is an important role for scaffolding, which needs to ensure prior learning is resituated in new contexts.

Sutton (1992) suggests that teachers should spend time talking about the words they use to support the continuous meaning-shifts that take place during learning. This includes passing on the agreed meanings of precise scientific terms and exploring the uncertainty of the more interpretive terms. Students should be given the opportunity to construct the meaning of these words and the concepts they embody.

Drawing attention to the range of meanings of ambiguous terms as suggested by Hayakawa (1990) is one way to bring about metacognition of the specific way a word such as development is used in the context of *Acetabularia*. It is important to communicate meaning through words, but learners also need to appreciate the range of use of a particular term, to avoid ambiguity.

This discussion acknowledges that progress in science involves building understanding of a scientific vocabulary. Advanced level students, and to some extent younger secondary students, should be initiated into formal language if they are to access the ideas of the discipline at higher levels. Being aware of how learners understand words, and their potential associated meanings implies an active role for designers in how they use language in resources.

Guideline 1 in the Quintana et al. (2004) framework provided a productive approach to thinking about the role of visuals and language used in software, but more detailed guidance is needed. 'Build on learners' intuitive ideas' in Strategy 1b is too vague to be practically useful to designers. The issues of shifting meaning and resituating scientific terms should be discussed more explicitly in the guidance. The framework also needs to provide guidance on how to create opportunities to introduce technical terms rather than replacing them. Replacing technical terms with alternative words is not a solution which bridges with prior learning, as it does not move students towards an understanding of technical terms.

The next section critiques Guideline 5 of the framework, suggesting that the type of metacognitive processes inferred in this guideline could also be applied to scientific terms and visuals. Spending time on establishing meanings of words and interpreting meanings communicated through visuals could contribute to establishing the entities which are, in turn, tools for thinking.

5.3.3 Testing Quintana et al.'s Guideline 5 to support the establishing of entities

The previous sections suggested that students' attention should be drawn to new scientific terms, and intuitive language should be used to 'bridge understanding' of these terms rather than replacing them. Metacognition of the role of formal language and the conventions of scientific formalisms should be viewed as elements of the pedagogic approach to learning through scientific inquiry.

Scaffolding strategies to bring about metacognition of inquiry processes suggested in Guideline 5 in the Quintana et al. (2004) framework could also be applied to these more generic but essential skills needed to communicate and interpret background science ideas successfully. Guideline 5 recommends providing expert knowledge about and rationales for scientific practices so learners can steer themselves strategically through an inquiry:

Guideline 5: Embed expert guidance about scientific practices.

(Quintana et al., 2004, p. 345)

Metacognition of the use of scientific language might involve introducing new scientific terms in a way that exemplifies or explains to learners how these words are used by scientists, and how meaning in a scientific context is different from other uses of the same words. This might involve scaffolding which actively encourages students to make sense of words and concepts which they encode. Metacognition of visual literacy in science might include attention to scale, interpretation of cross sections and use of scientific symbols. This introduces a tension between introducing new terms and using scientific visual conventions which serve as tools for developing ideas during learning, and the cognitive load imposed by unfamiliar language and representations. There is also a tension between providing and not providing guidance in terms of cognitive load.

Guideline 5 suggests that metacognition of processes is introduced by encouraging discussion of the nature and rationale for their use. A similar discussion of the nature and rationale for the use of scientific language or visual models could develop more sophisticated skills in students.

Evidence of learning and barriers to learning relating to visuals and language used in the tutorial were linked with the Background Science (Section 4.2.1) and Contextual Science (Section 4.2.2) data categories. This has been discussed in terms of evidence for confusion about *Acetabularia*, but the affordances of visuals could be an alternative focus. There is

evidence in students' experiment plans for Question 6 and responses to Question 8 that they have assimilated information about the visuals and language associated with the Hammerling inquiry.

The analysis of data using the Quintana *et al.* (2004) guidelines shows that empirical data from students carrying out the tutorial can support decisions about the terms (and visual models) which need to be scaffolded. An implication of this is that design of educational resources should involve iterative development informed by principled analysis, piloting and revision stages. The Quintana *et al.* (*ibid*) scaffolding design framework has shown its utility in guiding this process of iterative design. The utility of the guidelines is in framing the analysis of data through the idea that language and visuals should be selected to bridge understanding. Where data showed barriers to learning, the framework suggests how additional guidance could be provided, through an interpretation of Guideline 5. Attending to background science ideas through an interpretation of Guideline 5 would not require revisions to the wording of the guidelines. The broader interpretation of Guideline 5 could be illustrated through relevant software in the framework.

The next section discusses the guidance from the Quintana *et al.* (2004) framework which illuminates the data on the second section of the revised task model (see page 134).

5.4 Using the methods of scientific inquiry and reasoning to manipulate the entities, to collect data and to make inferences from the data

The task model elements involved in the scientific inquiry represented in the *Acetabularia* tutorial include the specific techniques and processes of Hammerling's experiments on *Acetabularia*. These provide the context for applying inquiry processes of collecting and analysing data leading to conclusions. Students' conclusions and explanations draw on theories about how the nucleus controls development.

This section discusses the utility of the Quintana *et al.* (2004) framework in illuminating scaffolding design to support students' understanding of the inquiry question, the techniques and processes of the Hammerling experiments, and the reasoning processes needed to make inferences from the experiments.

Table 5.3 Task model elements involved in scientific inquiry

<i>Narrative</i>	<i>Relevant prior learning</i>	<i>Background science</i>	<i>Contextual science</i>	<i>Science inquiry processes</i>
<i>Acetabularia</i> is large enough that it can be manipulated to investigate which part of the cell controls development.			2. <i>Acetabularia</i> is ideal for this type of inquiry, because it is large enough to dissect and manipulate.	
Scientific inquiry processes lead to the deduction that chemicals produced by the nucleus move into the cytoplasm and control development of the hat in <i>Acetabularia</i> .			3. A complete cell develops from any cell part that has the nucleus present, or from parts to which the rhizoid containing the nucleus has remained attached after removal of the hat. 4. A chemical signal travels between the nucleus and the cytoplasm, and these chemicals in the cytoplasm determine development of the cell parts.	1. Analyzing data (observations). 2. Constructing explanations.

5.4.1 Testing Quintana et al.'s Guideline 3 to support an understanding of the inquiry question

Quintana et al.'s (2004) Guideline 3 suggests that students can learn about phenomena through manipulating models to reveal their underlying properties:

Guideline 3: Use representations that learners can inspect in different ways to reveal important properties of underlying data.

(Quintana et al., 2004, p. 345)

Guideline 3 deals with the challenge learners face when making sense of representations of scientific phenomena. It suggests how representations such as graphs, equations and scientific diagrams can bridge between scientific formalisms and the phenomena they encode through functionality that allows students to manipulate and inspect the representation. The representations exemplified in the framework can be manipulated to reveal the properties of the underlying data. Quintana *et al.* (*ibid*) suggest that it is through manipulation of these models by changing variables that students make sense of the phenomena represented.

Manipulating *Acetabularia* to reveal outcomes of the experiments

The representation of *Acetabularia* in the tutorial is not a mathematical model which can be manipulated to show relationships between variables. In this way it differs from exemplifications under Guideline 3. However, animations following the drag and drop manipulables provide the observables which constitute the data from the Hammerling experiments.

Guideline 3 suggests that making sense of the connection between intervention and outcome is achieved through allowing students to carry out the manipulation of a model. The manipulables of *Acetabularia* exemplify a reinterpretation of Guideline 3, by revealing how *Acetabularia* develops as a result of experimental procedures. This is a reinterpretation of the guideline that reflects the needs of biological rather than physical sciences, where manipulations reveal observational data rather than mathematical data and relationships.

Students 'dissect' the *Acetabularia* visual using the scalpel tool provided, and drag the cell or cell part over to a Petri dish where it develops. There is evidence in students' answers to Question 6 that they can apply the techniques and processes of the Hammerling experiments to plan a new experiment. This suggests that students can predict the outcomes of these planned interventions (see data in Section 4.2.3), for example:

... remove nucleous from both plants 3. Insert AC nucleous in AM plants and viseversa.
4. Put them in petri dishes and see what hats they grow. [JF's written plan in Question 6]

The data suggests that, through the manipulables in the tutorial, students learn to link interventions such as transplanting the nucleus with outcomes such as developing a hat.

Entering into an inquiry

The emphasis in Guideline 3 is on students learning through manipulating representations. The idea underpinning Guideline 3 is that, by inspecting a representation, important

characteristics of the phenomena or patterns in the data are revealed. Strategy 3c 'Give learners "malleable representations" that allow them to directly manipulate representations' (Quintana *et al.*, 2004, p. 356) suggests that immediate feedback from these interactive models can make abstract concepts 'more understandable'.

The Question 6 written plans and post-tutorial data show that students can articulate the processes of the Hammerling experiments and their outcomes having used the prescriptive drag and drop manipulables available in the *Acetabularia* tutorial (see the example from JF's plan, above).

What the data also shows, is that students develop explanations of the observed phenomena, and that without sufficient scaffolding students' explanations can result in misconceptions. For example, there are misconceptions evident about where the genetic material is in *Acetabularia* as students explain Hammerling's Experiment 4 (see Appendix 6):

... some genetic material is stored in the cytoplasm + chemically transported to the tip.

Fitting the drag and drop manipulables with Guideline 3 extends the scope of the framework, showing how observables of biological phenomena can reveal patterns in outcomes, just as the mathematical models currently exemplified under this guideline reveal patterns in quantitative data. Guideline 3 suggests that a suitably designed tool could allow students to explore the phenomenon of development in *Acetabularia* more openly. This could allow students to test their own ideas and process the results of their actions rather than triggering a set piece presentation of an experiment plan.

An implication from evidence for misconceptions being introduced through the inquiry in this study is that design of tools which allow students to manipulate representations to develop an understanding of the relationship between variables needs to take place in the context of explanatory scientific models. How and when to present the scientific models which are being tested in a particular inquiry is a challenge for scaffolding design in software development and in lesson sequence planning more broadly.

Windschitl *et al.* (2008) suggest that students engage with the context of an inquiry more effectively if they have been given the opportunity and resources to develop a tentative model of the phenomenon being investigated. Struggling with a problem before being told the solution may make students more receptive to the explanation of the problem, even if their own interpretations are not accurate (Schwartz and Bransford, 1998).

There is evidence that students do have predictive models as they plan their experiments (see data on *Constructing explanations*, Section 4.2.3 and Appendix 8, point 2). The following utterance implies a predictive model where the nucleus controls development:

...take the nucleus out of it and see if it grows properly or not?

Students' discussions and their written answers as they plan an experiment in Question 6 (see data from Section 4.2.3) suggest this activity surfaces students' understanding of the inquiry question:

... we will see if the nucleus creates a hat corresponding to its species in the new plant ...
[written answer in Question 6]

Discussions of Experiment 4 following students' planning of this experiment in Question 6 supports Windschitl *et al.* (2008) and Schwartz and Bransford's (1998) findings. Students are stimulated to consider the outcomes of Experiment 4 more deeply than previous experiments, having thought through what they are trying to test and how to carry this out in their own plans:

FF ... the new hat corresponds. Oh yeah cos just like this one's got that nucleus, it's just got a different stem

IF Well why did the other one grow?

FF That's just like the intermediate hat it's just like the first hat that grows is always the same for both or something like that ... [FF and IF discussing the outcomes of Experiment 4].

Planning and implementing a virtual experiment could be used to encourage students to engage with the inquiry problem earlier in the tutorial. Students' observed difficulties in explaining the outcomes of the Hammerling experiments could be a result of not appreciating the context of the inquiry, or not having robust models which support sense-making about the observations.

Section 5.3.2 discussed the visual cuing of scientific ideas through the representations at the core of visuals, visual organisers and animations in ICT tutorials. Visual cuing has also been studied in relation to the representation of systems and the dynamic relationships between components of systems which can be revealed by the type of manipulable models being discussed under Quintana *et al.*'s (2004) Guideline 3. Ok-choon Park (1998) compared the cuing effects of three types of visual display in instruction on structures and functions of electronic circuits and their associated trouble-shooting procedures. One of the findings was that in a comparison of static graphics, static graphics which suggested the dynamic functions of the system through visual cues and animations, there was no significant

difference between the graphics with cues to signal dynamic relationships and the animations. Park explained this in terms of whether the visual cues stimulated context-free component-based mental models of electronics, or system-bound mental models based on whole circuits.

The data on students' understanding of *Acetabularia* suggests that students' appreciation of the components of the cell does not necessarily result in a mental model of the 'whole system'. Cuing the dynamic relationship between the parts of the cell and development of new parts of *Acetabularia*, whether through still images or animations, needs to be considered with regard to the need for students to appreciate the whole organism system alongside the role of individual components within the system.

This section concludes that manipulables can embody and reveal the outcomes of biological experimental observations. But, it also concludes that interpretation of these observables will not necessarily follow automatically, even if students have thought through their own predictive models and plans for an inquiry. A more open inquiry tool could engage students more deeply in the inquiry question, but the gap between their intuitive ideas and authoritative scientific explanations still needs to be bridged. Consideration of the scaffolding involved in a more open inquiry tool could broaden the scope of Guideline 3 beyond tools which interface with mathematical models. In the suggested tool, manipulations reveal outcomes resulting from manipulations of an organism. This discussion also suggests that scaffolding needs to set any exploration of malleable visuals in the context of the wider inquiry questions, along with the background science concepts and processes that allow students to interpret any findings. The manipulables also need to cue the important components of the organism along with an appreciation of the whole dynamic system of a developing cell. An implication is that scaffolding needs to be positioned in a broader pedagogic approach to learning through inquiry. This idea is developed further in Chapter 6.

The next section explores the scaffolding guidance for inquiry tasks set out in Guideline 4 of the Quintana *et al.* (2004) framework.

5.4.2 Testing Quintana *et al.*'s Guideline 4 to support scaffolding of complex inquiry tasks

Producing conclusions backed by evidence

The process of linking evidence and conclusions is supported throughout the *Acetabularia* tutorial, for example through the multiple choice questions following the experiments. The

focus for this stage of the study leads from data showing that SNAB students demonstrated problems in drawing on background science to produce explanations which provide causal mechanisms. Linking evidence from experiments with conclusions is an important aspect of the inquiry process of developing scientific explanations, but advanced level students need to go beyond simple inferences from the data.

The student data shows that the tutorial allows students to develop skills of reasoning separately from the 'noise' of a wet practical, where the techniques and processes of the experiment can dominate. Specifically, there is evidence that the multiple choice questions in the tutorial stimulate students to discuss the evidence from experiments in relation to the conclusion statements which are suggested in the questions (see data from *Constructing explanations*, p.120).

It is worth noting that this type of discussion is in contrast with students' frequent experience of practical inquiry. Often the collection of data and its presentation dominate practical lessons compared with discussion about the inferences from the experiment. Leach and Scott (2002) suggest that these types of opportunities for internalisation through discussion need to be built into any teaching sequence that involves an empirical inquiry. Teachers should aim for more of a balance between the setting out of the story of science (whether through inquiry or expositions of theories) and the talking. Stimulating this type of discussion is a potential affordance of electronic tutorials that is considered later with reference to Guideline 7 (see Section 5.5.1).

Chapter 4 discussed evidence showing that, by the end of the tutorial (as they carry out Question 8), SNAB students were able to link evidence and conclusions from the Hammerling experiments (see data from *Constructing explanations*, p.120). This data suggests that scaffolding of this specific inquiry process in the tutorial can be considered successful, and the fit of the evidence with the Quintana *et al.*'s (2004) Guideline 4 is tested in this section.

Guideline 4 in the framework was developed in response to evidence that students lack knowledge about inquiry processes and the procedures for performing them:

Guideline 4: Provide structure for complex tasks and functionality.

(Quintana *et al.*, 2004, p. 345)

The multiple choice questions in the tutorial scaffold the stage in the hypothetico-deductive process of scientific inquiry where observations lead to conjectures or hypotheses, aiming

to explain the observations. Hypotheses do not emerge automatically from the data, but rely on a combination of background knowledge, creativity and imagination. Frequently, this step is underestimated by teachers and educators with expert knowledge of the discipline (Millar, 2004).

If students are unlikely to arrive at scientific conclusions themselves, it is appropriate to provide these as part of the scaffolding of building explanations. Lack of expertise could lead to students' thinking being misdirected if they do not notice what is important in the evidence of the Hammerling experiments, for example.

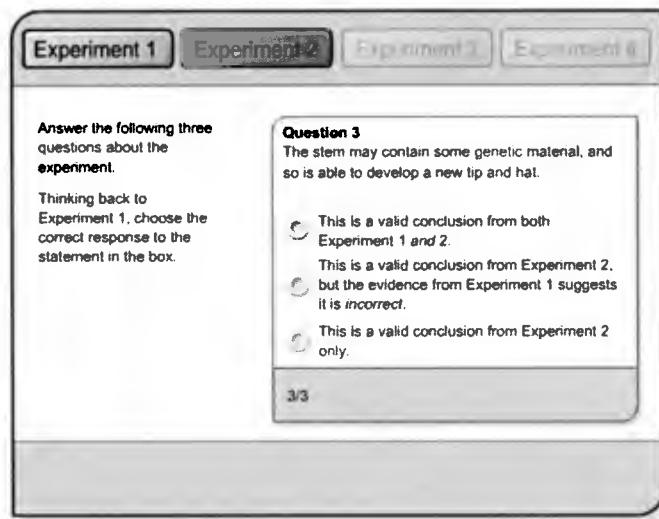
The multiple choice questions are discussed below in terms of two affordances suggested by the strategies under Guideline 4: the questions restrict the task by completing some elements, and they provide activity spaces underpinned by a heuristic for producing conclusions backed up by evidence.

Restricting the tasks in the SNAB tutorial

Scaffolding strategy 4a, 'Restrict a complex task by setting useful boundaries for learners' (Quintana *et al.*, 2004, p. 345), aims to save students' time and effort on processes which are not central to the learning outcome. By reducing the complexity of the inquiry, the potential barriers to learning imposed by excessive cognitive load are reduced, making learning more effective.

Strategy 4a is exemplified in the framework by software tools which partially complete the task of organising and presenting the data students need to make sense of the inquiry. This saves time and effort by focussing students on the most salient features for their attention. The multiple choice questions restrict the task of producing evidence-based conclusions by providing conclusions which students have to match with evidence they identify from the experiments.

Figure 5.2 Multiple choice question after Experiment 2



The questions (for example, those in Figure 5.2) are points in the tutorial where students are supported in making inferences from the Hammerling experiments. The questions provide support as students establish the conclusions for each experiment before they continue to the next. This is an important function for scaffolding, as the narrative of the experiments incrementally builds the evidence for the role of the nucleus in development. Support is necessary for the complex task of considering the evidence from several experiments. But scaffolding strategy 4a introduces a tension which is not discussed in the framework. Designers have to make a decision on *how much* to restrict a task. Reducing cognitive load to make learning more effective must be balanced with maintaining the intellectual integrity of the inquiry tasks.

Cognitive load theorists point to the importance of germane cognitive load, which stimulates mental activity that contributes to schema formation (Sweller, Van Merriënboer and Paas, 1998). The multiple choice tasks in the tutorial deconstruct the reasoning process to the extent that little remains for students to do. The data can be interpreted by suggesting that the confusion some students show when they engage with the questions is due to the cognitive load from the complex logic task which the wording of the questions imposes (see data from *Constructing explanations*, from p.120):

... oh God I really don't know this time... [FF struggling to make sense of the response options on screen 13]

This complexity is exemplified in the question in Figure 5.2, where evidence from two experiments has to be considered simultaneously, along with three different logic statements.

The extraneous cognitive load imposed by the construction of these questions could reduce the working memory capacity available for the main task of linking evidence and conclusions. Evidence for the difficulties students experience with these questions includes instances where students are clearly guessing the answer (see data from *Constructing explanations*, from p.120):

Doh. Maybe it's er that one [DF appears to guess the next response after an incorrect answer message on screen 12]

Along with the evidence of confusion over the question format, this data supports the idea that the multiple choice questions in the tutorial need to be revised.

The conclusion from this discussion is that the data illustrating students' responses to the task of linking evidence from the Hammerling experiments with conclusion statements fits scaffolding approaches suggested in Guideline 4. Literature on the nature of scientific inquiry can be used in conjunction with Guideline 4 to suggest specifically how the task should be restricted. In the case of linking evidence and conclusions, the literature suggests it is appropriate to restrict by providing conclusions where students can't be expected to reach these themselves (Millar, 2004). This supports the earlier discussion of Guideline 3, which concluded that students should be provided with scientific explanations which do not automatically emerge from the data.

Guideline 4 does not draw on cognitive load theory as a rationale for restricting inquiry tasks. A consideration of the literature on cognitive load in association with Strategy 4a is helpful in suggesting extraneous cognitive load should be minimised (Sweller and Chandler, 1994) by revising the wording of the questions and the nature of the logic task that students have to engage in. Germane cognitive load should be optimised (*ibid*), by restricting cognitive demand to tasks that are directly relevant to learning. For example, the task of matching single aspects of evidence and conclusions involves germane cognitive load, so should be maximised. Carrying out complex logical processes, such as deciding which of two experiments supports a conclusion and which refutes it, should be reduced to minimise extraneous cognitive load.

Testing Strategy 4a against the data suggests that this guideline needs to provide more detail on how much to restrict a task, and which aspects of a task it is useful to restrict.

This section has shown how more explicit reference to the application of cognitive load theory and the literature on the nature of scientific inquiry might allow designers to apply Guideline 4 with greater insight. The guidance in the framework could include annotations which reference literature that contributes to design decisions. These references will vary depending on the context of the design but may be from outside the domain of science inquiry learning. The framework could provide design case studies illustrating how the guidelines and any applications of broader literature have been applied.

The next section considers the second affordance of the multiple choice questions in the tutorial, using strategy 4b in the framework.

Using ordered and unordered task decompositions

Strategy 4b describes how both ordered and unordered activity spaces can provide scaffolding for inquiry tasks:

Strategy 4b: Describe complex tasks by using ordered and unordered task decompositions.

(Quintana et al., 2004)

Activity spaces represent task-specific actions which are part of a logical sequence. In an educational resource activity spaces allow support to be provided for the constituent tasks of a process, arrived at through task decomposition. For example, activity spaces can be defined to represent the sequence of separate tasks involved in an inquiry. Ordered activity spaces exemplified in the Quintana et al. (*ibid*) framework by software tools under Strategy 4b involve diagrams which make the stages and sequence of a task explicit. With unordered activity spaces, students have to determine the order in which activities are carried out.

Strategy 4b provides further insight into scaffolding provided by the multiple choice questions in the *Acetabularia* tutorial. This strategy provides a view of the questions as representing ordered activity spaces which take students through a heuristic for developing conclusions supported by evidence. A post-hoc analysis of the sub-tasks which these questions imply leads to the following suggested heuristic:

- 1) Identify and interpret the significant aspects of the data (evidence from observations).
- 2) Produce an initial statement of conclusion (hypothesis) which offers an explanation of the data.

- 3) Compare the conclusion statement with the evidence from the experiment.
- 4) Identify evidence from the experiment which supports the conclusion statement.
- 5) Decide whether any evidence from the experiment refutes the conclusion statement.
- 6) Accept, reject or refine the conclusion statement in the light of the evidence.
- 7) Carry out stages 1-6 with evidence from other experiments.

Stages 1-6 of the task model form the heuristic for producing a conclusion from a single experiment. The structured reasoning tasks scaffolded by the multiple choice questions in the *Acetabularia* tutorial involve activity spaces 1-7, as students must consider evidence from more than one experiment to support or refute the conclusion statements provided. Stages 1 and 2 of the heuristic are already completed in the type of multiple choice questions shown in Figure 5.2 (p.160).

The data provides evidence that students are later able to carry out the other stages of the heuristic in the less structured task in Question 8. They produce their own conclusions from the Hammerling experiments (although these draw on those provided in the tutorial), and select evidence which supports or refutes these conclusions (see data from *Constructing explanations*, from p.120). For example, EM's "Chemicals can be stored in stem to develop new hat" is supported by "Experiment 4: Rhizoid was swapped species but new hat corresponding to the stem species" in the written answer to Question 8.

The stages of this heuristic include processes referred to by Quintana *et al.* (2004), but the framework does not provide a single exposition of the ordered activity spaces involved in constructing an explanation. The scaffolding design framework assumes designers have the knowledge of the domain and its associated pedagogies to develop the appropriate task models for inquiry processes, and to decompose these to produce appropriate constituent activity spaces.

The needs of learners relating to individual tasks may not always be obvious to teachers and designers, as this depends on multiple factors including the demand of the science topic and students' prior learning. A metacognitive commentary from designers to make the process

involved in designing activity spaces explicit would be a useful addition to the framework for future designers.

As in the previous discussion on Scaffolding Strategy 4a, this consideration of strategy 4b demonstrates the role of empirical data, along with task decomposition, in determining the demand of a task. It also demonstrates the utility of the scaffolding design guidelines in the analysis of empirical data and evaluation of the efficacy of scaffolding tools.

Apprenticing students in the processes of the discipline

The rationale for strategies under Guideline 4 of the framework references the literature on learning through apprenticeship. In this learning approach, students take part in authentic but restricted workplace practices. Restricting allows apprentices to take part in tasks which are similar to those which experts might carry out.

School science inquiry is rarely authentic, as discussed in Chapter 2 (Section 2.4). There is often a particular learning outcome that the teacher knows, and which students are guided towards. Where learning through science inquiry can be compared with apprenticeship is that both types of learning involve a set of practices of the domain which are largely tacit 'knowledge in action' (Millar, 2004, p. 2). As in apprenticeship, learning through science inquiry may involve tacit teaching of the role of individual inquiry processes (Lave and Wenger, 1991).

The previous section suggested that the *Acetabularia* tutorial may provide implicit guidance through exemplifying the heuristic for developing valid conclusions. Through carrying out this heuristic repeatedly in the multiple choice questions, students develop a tacit understanding of what valid conclusions are and how to develop them, by exemplification rather than explanation.

In addition to the data from Question 8, the post-tutorial interviews provide some evidence of students' appreciation of how conclusions are structured in a situation with no scaffolding. When asked to explain what happened in the Hammerling experiments, students produced statements which demonstrate that conclusions have to be backed up by evidence (see data from *Constructing explanations*, from p.120).

The post-tutorial tests carried out by students from Centre B also provided evidence that more students produced explanations of control by the nucleus in the form of a conclusion

backed up by evidence than had been the case in the pre-tutorial test (see data from *Constructing explanations*, from p.120).

A conclusion from this consideration of Strategy 4b is that the Quintana *et al.* (2004) framework fits the data showing how students are supported as they develop explanations in the tutorial. The suggestion is that Strategy 4b could be exemplified in the framework to show how a heuristic for an inquiry process can be implied through activity spaces, and that this can bring about tacit learning of the heuristic. This conclusion is supported by evidence that students who carry out the restricted task in the multiple choice questions are later able to apply the task in a less structured situation (in Question 8).

Guidance at a sufficient level of granularity

The decomposition of tasks and their nested sub-tasks must guide scaffolding at the appropriate levels. This study has shown that what is meant by 'sufficient granularity' of scaffolding may only be revealed through analysing data from students as they study, as this enables barriers to learning to be identified.

Analysis of the tasks in the multiple choice questions involved consideration of 'explaining' at a level of granularity beyond the original decomposition discussed in Chapter 3. The original task model (Section 3.2) was produced by considering the main tasks which might be involved in a complete inquiry (with reference to the AAAS concept maps). These included the application of background science, contextual science and inquiry processes. The task model for 'explaining' was identified at the level of 'constructing explanations' only.

In the Quintana *et al.* (2004) framework, inquiry tasks are not decomposed to a level that would be useful to designers of scaffolding. For example, there is no reference to the need to draw on background science ideas to produce causal explanations. This is partly a function of the framework's generally applicable guidelines which must apply to a wide range of inquiries at a range of levels of learner. Defining each individual task at the detail of sub-tasks is beyond the scope of a framework that is workable across any software tool which scaffolds science inquiry. But, the challenge of using the framework to make decisions about scaffolding design raises an issue which may apply to other aspects of generalised guidance: the sparsity of guidance available on individual inquiry tasks makes applying the guidelines in this specific context problematic.

A conclusion from this discussion is that references to how designers have dealt with this issue of defining the task models, and of task model granularity should appear as an

annotation within the framework, along with the software examples. This would help future designers using the framework to be made aware of the multiple layers of the task of designing scaffolding. The task model for the *Acetabularia* tutorial provides such an example, where the task model for explanations developed during the process of analysis and revisions.

The discussion on decomposing scientific explanations raises the issue of the model of the scientific method which underpins the pedagogic approaches to learning through science inquiry. Designers should not assume that supporting inquiry processes will lead to explanations. The data from this study suggests there is a need to provide students with models with which they can make sense of an inquiry, and scaffolding to support recruitment of explanatory models from prior learning.

Defining the pedagogic content of the domain is beyond the scope of most design researchers. The science education community should be involved more broadly in developing descriptions of the main inquiry tasks. An agreed set of detailed task models are needed for designers to frame their scaffolding designs for science inquiry learning.

The methodology used in this study shows how the definition of a task model develops iteratively during scaffolding design. An initial task decomposition was used to match scaffolding strategies in the tutorial with the main constituents of inquiry that organise the scaffolding design framework (sense making, process management and articulation and reflection). More detailed analysis of the task model became appropriate once empirical data suggested barriers to learning at particular points in the tutorial. In this way the design process is revealed as a complex process which refers to the guidelines, the student data and the tutorial's task model. Each of these elements contributes to insights into how learning is being supported, to where more support is needed in the tutorial, and where a clearer definition of what is involved in learning in a particular domain is needed.

The next section goes on to discuss the third category identified in the revised arrangement of the task model, which involves making links between a specific inquiry and the background science theories which make sense of its findings. This builds on the discussion so far, where the task of producing scientific explanations has been deconstructed to include two aspects: linking simple conclusions and evidence, and developing causal explanations. Consideration of the scaffolding needed to support students as they build increasingly broader and more complex schemas for scientific explanations is carried out with reference to Quintana *et al.*'s (*ibid*) Guideline 7.

5.5 Supporting science explanations

5.5.1 Testing Quintana et al.'s Guideline 7

This section discusses the concern raised by the data from this study showing that learning from the *Acetabularia* tutorial does not lead to students making connections with prior learning to explain the causal mechanisms of development. Earlier sections in this chapter have discussed how the data shows that students use process skills of making valid conclusions by the end of the tutorial, and that they can make simple inferences from the Hammerling experiments.

There is an assumption that, if the tutorial is to contribute to students' broader understanding of development, links with prior learning, including transcription and translation, will take place later. The elements of the task model, which should be involved in using the specific context of the Hammerling experiments to build broader and more complex schemas for cells and development, are shown in Table 5.4.

This section of the analysis tests Quintana et al.'s Guideline 7:

Facilitate ongoing articulation and reflection during the investigation.

(Quintana et al., 2004, p. 345)

Guideline 7 encourages articulation as a central process in planning, monitoring and making sense of inquiry. It also encourages articulation and reflection in the production of epistemic products of science, including explanations.

Table 5.4 Task model elements for developing broad schemas for science topics

Narrative	Relevant prior learning	Background science	Contextual science	Science inquiry processes
This is a specific example of the role of the nucleus in all cells. It can be explained using theories about how	Genes are in the nucleus of a cell. Genes are responsible for proteins produced in a cell (through transcription and translation).	2. The nucleus contains the cell's genetic material. 3. The genetic material contains the code which controls which proteins (and other chemicals) are made		2. Constructing explanations.

the nucleus controls which proteins are produced in cells.	Proteins in the cytoplasm control cell processes, including development.	in the cytoplasm. 4. Chemicals in the cytoplasm control the cell's activities (which chemical reactions take place). 5. Development of characteristics (including specialised structures in the cell) is controlled by chemicals in the cytoplasm.		
--	--	--	--	--

The content of articulation and reflection

The literature suggests that learning should contribute to the continuous refinement of students' schemas to develop big, overarching ideas of science (Anderson, 1983; Leach and Scott, 2002; Bell *et al.*, 2010). Students' confusion about what *Acetabularia* is becomes significant in the light of evidence for their difficulty in describing the overall process of development in the post-tutorial interview and test data (see data from *Constructing explanations*, from p.120). This evidence is interpreted as a failure to make links with relevant prior learning about cells, genetics and transcription and translation, possibly as a result of not appreciating that *Acetabularia* is a single cell.

Quintana *et al.*'s (2004) Guideline 7's strategy 7c promotes 'articulation and reflection' during sense making:

Strategy 7c: Provide reminders and guidance to facilitate articulation during sense-making.

(Quintana *et al.*, 2004, p. 345)

This strategy builds on a constructivist view of learning, which sees the act of publicly reflecting on and articulating understanding as an important stage in learning (Scardamalia and Bereiter, 1991). It is left to the designer to decide the precise content of the reflection and articulation. The software examples in the framework do not provide any rationale for designers' selection of this content. The data on students' fragile learning and evidence of difficulties with resituating learning discussed in Sections 5.3.1 and 5.3.2 suggest articulation and reflection should be involved in developing causal explanations which draw on background science.

This section suggests how designers could go about supporting the content of students' articulation and reflection, stimulated by software tools. For example, students should be encouraged to articulate the links between their observations from the Hammerling experiments and their existing schema for transcription and translation. Transcription and translation should account for the production of controlling chemicals by the nucleus of *Acetabularia*. The overarching story of transcription and translation provides the explanation of how the nucleus exerts control, not simply that it does exert control.

Quintana *et al.*'s (2004) descriptions of what is meant by a scientific explanation are drawn from the literature. These descriptions should support designers in knowing what the products of scaffolding explanations might include. In the discussion of Guideline 7, explanations are described as linguistic features which 'refine or expand on ideas' or 'infer consequences', 'explore multiple hypotheses', and 'present coherent assertions, provide evidence, and justify connections between claims and evidence'. Quintana *et al.* (*ibid*) also point to learners' problems with distinguishing between descriptions and explanations, and how learners may omit justifications or reasons when they discuss causality.

Developing explanations presents a considerable cognitive challenge for science students as they draw on the two domains of science inquiry processes and background science. Both domains are strongly involved as students interpret data. Teachers' common belief that ideas will 'emerge' automatically as students make observations and analyse data ignore the hard, creative work based on expert knowledge employed by professional scientists as they develop scientific theories (Leach, 1998; Millar, 2004; Abrahams and Millar, 2008).

Ogborn *et al.* (1996) describe explanations in terms of a set of nested entities. Entities which are protagonists in the inquiry are one type of explanation that students need to understand. In the *Acetabularia* tutorial these entities include *Acetabularia*, cells and cell structures including the nucleus, development, and the individual techniques which are used in the Hammerling experiment. Each of these contains further nested entities, and each entity nests within more than one higher level entity. For example, 'DNA' nests within 'nucleus' and 'nucleus' nests within both 'cell' and 'development'.

The discussion on defining task models for inquiry processes in the previous section becomes relevant here: the task model for scientific explanations must draw on what has been written about 'explaining' in the wider literature if the task model is to be of sufficiently detailed granularity to support scaffolding design. As discussed in Chapter 2, Ogborn *et al.* (1996) suggest that it is not useful to distinguish between abstract ideas and

concrete entities. Each of these is a chunk of meaning which serves as a tool for thinking and explaining. How to establish these entities is less clear, as understanding does not necessarily lead directly from experience. It is this process of how educators go about developing understanding of an entity which needs guidance as part of scaffolding for science inquiry learning.

The data show that scaffolding designed to support students' sense making needs to acknowledge the different levels of explanation that exist. Ogborn *et al.* (1996) draw attention to the difference between everyday explanations, which are about familiar entities doing familiar things, and scientific explanations, which are of an unknown world of entities such as molecules and photons. Explanations in school science are the tip of an iceberg of nested explanations. If a student carries out an experiment on dissolving, the explanations for what they observe include all the theory on states of matter, molecular theory and thermodynamics. Dissolving can clearly be understood at different levels, as can development in *Acetabularia*. The need for phenomena to be explained is not necessarily evident, as students may not have any idea that things they observe can be explained (Ogborn *et al.*, 1996).

The conclusions which students reach by Question 8 are guided by the heuristic provided in the multiple choice questions. This was discussed in the section on using ordered and unordered task decompositions on p.162. Students' conclusions follow both the form and level of complexity of the explanations provided in the questions. For example, in Question 8, LF's conclusion "All the genetic material is contained in the nucli" is supported by evidence "Experiment 3: the stem that contained the nuclei from the rhizoid grew into a complete new cell", and "Experiment 4: the hats that are developed corresponds to the nucli that is present." There is no attempt to go beyond these simple inferences from the experiments.

Following Ogborn *et al.*'s (1996) argument, scaffolding needs to start from the position of pointing out what needs to be explained. This builds on discussions in this chapter on Guideline 4, which suggested that scaffolding should focus students' attention on the inquiry question. Where explanations go beyond simple conclusions to involve causal mechanisms, an inference from this study is that the models which offer explanations at this level need to be provided or at least strongly signposted if students are to use them to explain the phenomena observed in an inquiry.

Quintana *et al.*'s (2004) Guideline 7 contributes the idea that articulation and reflection are important during sense making. The data from this study suggest that guidance for scaffolding design should encourage designers to consider in detail the components of the explanation which need to be recruited.

The data from this study suggests that students need support to recruit the appropriate entities as they construct explanations at different levels. Ideas from constructivist views of learning and situated learning suggest that explicit scaffolding aimed at resituating prior learning from previous topics needs to take place as students develop explanations for observed phenomena (Lave and Wenger, 1991). Establishing the entities may draw on prior learning, in which case 'establishing' means supporting students to resituate the ideas into the new context of a science inquiry. SNAB students may benefit from scaffolding which establishes 'cell', 'protein synthesis' and 'unicellular organisms' in the context of *Acetabularia*, for example. When and where to introduce the relevant entities is still a challenge for designers.

Sutton (1992) suggests that practical science inquiry should engage students less in the task of interpreting nature directly from data, and more in critiquing what scientists have said in the past (accepted scientific theories) using data from their inquiries. This supports the idea that theories or models need to be provided as a tool for students' explanations, but that scaffolding should prompt students to discuss (and critique) these explanations in the context of their own inquiry.

Windschitl *et al.* (2008) also suggest that learners need a model to frame their investigations, even if this is a faulty model that they have constructed themselves. Without this, learners' investigations may be systematic and objective, but devoid of conceptual content that could make sense of the outcomes. Windschitl *et al.*'s (*ibid*) theory resonates with Ausubel's (1968) 'organising ideas' that orientate students' thinking. It also reinforces the idea that an inquiry should contribute to the bigger picture of science (Anderson, 1983; Leach and Scott, 2002; Bell *et al.*, 2010) by using models to explain phenomena in different contexts, and the idea that background science theories should be considered as the data from which an inquiry emerges (Solomon, 1999).

Sutton's (1992) idea of introducing theories and encouraging students to critique them in the light of their own inquiry is guidance that could be provided to designers. This is an example of where scaffolding for articulation and reflection could stimulate students to consider specific content. Windshitl (2008) contributes guidance on introducing a model for

reference, and Solomon (1999) suggests the framing of the inquiry should be carried out throughout, rather than before or after an investigation. All these references from the literature lead to the conclusion that students need authoritative expositions of science, but that they also need the opportunity for inquiry and for developing their own constructs of science narratives through discussion.

Other studies suggest that there is a role for the type of open inquiry discussed with reference to Guideline 3, but as a stage which precedes an exposition of explanatory theories, whether this is by the software or the teacher. Thompson and Zueli (1999) suggest that an exposition about the phenomenon is ideally only given after students have struggled with questions or problems, so are in the position of needing an answer. Wells (2008) also asserts that scientific concepts are learned most effectively when the learner is deeply engaged in solving a problem, so explanations of the concepts function as semiotic tools for achieving a solution. Schwartz and Bransford's (1998) study shows that particular analytical tasks alert students to focus on concepts which offer potential solutions to the tasks in subsequent lectures. An open inquiry tool could create a similar readiness for being 'told' the background science that makes sense of the inquiry, and scaffolding tools could stimulate discussion of problems in need of a solution.

This discussion suggests *what* students might productively discuss and *how* the discussion might be set up. It suggests *when* the explanatory theories might be introduced. This guidance goes beyond the detail in Guideline 7 of the framework. The issue of how to build this type of discussion of the pertinent literature into a generic framework has been discussed earlier. The solution here may be similar to that proposed in the previous section: case studies should appear as an annotation within the framework, along with the software examples which exemplify how designers have interpreted the scaffolding design guidelines. This technique is already used to an extent in the framework, but the annotations in the framework only describe the tools which illustrate the strategies in the framework. The suggestion is that annotations should make relevant literature explicit where this has underpinned a particular approach to interpreting the guidelines.

Prompting articulation and reflection

In their discussion of Guideline 7, Quintana *et al.* (2004) identify a barrier to learning from the literature described as students not knowing when articulation and reflection might be appropriate to support learning through inquiry. The data from this study shows that students are stimulated to articulate inferences from the Hammerling experiments by the

multiple choice questions. There are instances where students refer back to the experiments as they consider the questions (see, for example, data in Section 4.2.2, point 3).

This effect of the questions was predicted by the deconstruction of the tutorial, as they were designed to encourage discussion, and represent scaffolding for this purpose at relevant points in the tutorial. In this case, the empirical evidence supported the conclusions from the task deconstruction, and shows a good fit with Guideline 7's generalised scaffolding strategies.

The data also shows that, when students make an incorrect submission for the multiple choice questions, there is often little discussion of why the question is wrong. Incorrect first submissions frequently lead to another 'guess' (see data in the section on *Constructing explanations*, p.120). In this case, the questions do not prompt useful reflection. This represents a fit with a similar barrier identified in the framework, where Quintana *et al.* (*ibid*) suggest that students focus on achieving quick outcomes rather than taking time to identify and reconcile disagreements. Schabe *et al.*'s (1991) work illustrates this phenomenon. They found that children engaged in science experiments often use the engineering model of experimentation, characterised by manipulating variables to produce a desired outcome, rather than the science model, where the goal is to understand causes and effects. An inference from testing this aspect of the guidance in the framework using the data is that the tutorial should provide feedback, prompts and hints to promote more productive discussion and to avoid students guessing the answers to multiple choice questions for initial and subsequent attempts.

Skinner (1954) used the principle of the immediacy of reinforcement of correct responses in the design of his early mechanised teaching machines, but later work found that this reinforcement does not have a positive effect on learning in all situations. Anderson *et al.* (1972) also found that immediate knowledge of the correct answer can lead to carelessness and inattention. Only giving students the correct answer after they had produced an answer themselves did improve performance.

These studies suggest that multiple choice questions should be designed with rich feedback rather than providing simple knowledge of whether or not a response is correct. The amount and level of feedback and guidance would need to be carefully designed and tested. McKeachie (1974) found that, where richer feedback provided students with the knowledge necessary for them to reach a solution to a problem, the students only made use of this

knowledge in situations where the task was difficult. In this situation, the time spent by a student on discovering the new knowledge in the feedback was worth the cost of the time taken for accessing the feedback.

This discussion of Guideline 7 has emphasised the need for designers to define the content of what students should be encouraged to articulate and reflect upon, and how this can be prompted effectively. Quintana *et al.*'s (2004) strategy 7b justifies the need for students to articulate explanations, as important products of science inquiry learning. Strategy 7d refers to explanations, descriptions and interpretations as epistemic products which learners need to create:

Scaffolding strategy 7d: Highlight epistemic features of scientific practices and products.

(Quintana *et al.*, 2004, p. 345)

This chapter has argued that scientific explanations are not simply products to be created by learners, but are the product of many years of work by scientists in the past. Learners can't be expected to create explanations, but these should be introduced to students as a framework for making sense of their inquiry work.

The next section continues the discussion on the guidance for designers on the content of articulation and reflection. It tests Guideline 7's Strategies for scaffolding epistemic products of the domain with reference to data on students' reaction to visuals in the tutorial.

Visuals as epistemic products

Quintana *et al.* (2004) refer to literature relevant to sense-making about *Acetabularia* through formal representations. The French sociologist and philosopher Bruno Latour (1990), for example, emphasises the encoding of expertise in scientific representations. He describes diagrams and symbolic notations as being produced through complex translations of knowledge. The idea behind Latour's work is that to produce a visual, the designer takes a position on how they see a particular entity, or the type of visual model which represents an idea. This surfaces the designer's interpretation of the phenomena, allowing others to compare it with their own ideas, and making it possible to discuss the ideas in a concrete way.

Visuals embody specialist knowledge, and assist knowing and learning by communicating and sharing the knowledge (Ewenstein and Whyte, 2005). Once *Acetabularia* is transformed into a visual representation for the tutorial, as Latour (1990) suggests, it provides a concrete

phenomenon which can be discussed. Students can articulate what they do or do not understand about a visual.

Quintana *et al.*'s (2004) Guideline 7 does not currently refer to the potential of visuals as epistemic products of science. The data from this study suggests that the visuals in the tutorial stimulate articulation about what *Acetabularia* is (see data in Section 4.2.2):

... that'll be the tip. Yes it doesn't have a head yet ... [LF and DM discuss the visual of a young *Acetabularia* on screen 4]

... so, it can really grow from the top but not the bottom ... [IF comments on the fully developed cell at the end of Experiment 2]

These utterances demonstrate that visual representations embody ideas that people can share and talk about. If scaffolding is to support students' awareness of how knowledge is constructed in the scientific community, students should be encouraged to articulate their sense making of the shared products of science, including visuals. Just as students need to know how scientists construct explanations to take part in the discourse of science (Lemke, 1990), they need to know how scientific representations are constructed. Scaffolding to highlight how the features of the visuals were arrived at and how they embody knowledge, might present a method for communicating the important background science that needs particular attention. This could be done, for example, by supporting students as they critique the visuals' effectiveness in communicating the relevant science.

The scope of Guideline 7 could be extended by including examples of visuals as epistemic products which people can share and talk about. This idea overlaps with the idea of stimulating metacognition of the use of language and visuals in the earlier section with reference to Guideline 5. In this case, Guideline 7 does not need to be revised, but it needs further annotation or exemplifications to include the idea of visuals as epistemic products under Strategy 7d.

5.6 Conclusions from the study

There are some general conclusions from this study about the scope and utility of the Quintana *et al.* (2004) scaffolding design framework. The framework provided a useful reference for analysis of the data. It allowed the scaffolding in the *Acetabularia* tutorial to be compared with similar approaches exemplified in the framework. The second stage of analysis concludes that the scope of the framework could be broadened to include electronic tutorials similar to the one used in this study, in addition to the software

currently in the framework that exemplifies scaffolding for open inquiry through practical work. This study also suggests extending the scope of the framework to emphasise scaffolding of background science within the existing guidelines, in addition to inquiry processes.

Testing the data against the framework illuminated the scaffolding approaches in the tutorial, helped to identify gaps in the scaffolding of the tutorial and suggested gaps in the framework.

The ideas discussed in this chapter suggest that a task design should ensure the learner understands the background science context for an inquiry by explicitly scaffolding understanding of the entities which are relevant to the inquiry. Tasks should engage students with an inquiry question, using approaches such as model-based inquiry to guide students' interpretations of the phenomena which they are exploring.

The Quintana *et al.* (2004) framework needs to provide more guidance on how to go about providing access to authoritative accounts of the background science relevant to an inquiry. While accepting that explanatory theories need to be provided, these should be preceded by early stages of inquiry. Inquiry sets up a readiness for learning or a 'time for telling' (Schwartz and Bransford, 1998).

This chapter referred to the importance of establishing scientific entities as tools for constructing explanations, through language and visual models. A conclusion is that interpreting scientific formalisms and language are skills which need to be taught, developed and practised rather than assumed in the design of software tools. Metacognition has been raised as a key aspect of learning through science inquiry. Guideline 7 could be extended to provide strategies which encourage students to reflect on how language and visuals are used to communicate science, and how an inquiry contributes to increasingly overarching scientific principles. Section 5.3.2 suggests an additional strategy could complement 1b, by referring to visual literacy and scientific models.

Explanatory theories need to be processed by students, who situate them into the new context as they make meaning of the inquiry. For example, if transcription and translation is suggested as an explanatory theory for control of development by the nucleus, students need to make the explicit link between transcription and translation and the chemicals in the cytoplasm of *Acetabularia*. It is this process of making links with explanatory science that needs to be scaffolded. The framework needs to provide explicit guidance for designing

scaffolding which shows how background science ideas are used to explain new phenomena, by resituating them into new contexts.

Designers need to base scaffolding on detailed decompositions which identify sub-tasks of inquiry processes. For example, the task of making links with explanatory theories might involve critiquing accepted scientific theories against students' own tentative ideas and with data from the inquiry. Scaffolding strategies for this purpose could be included under existing guidelines in the framework, but the underpinning task models of inquiry processes, need to be more explicit. In the context of explanations, discussed in this chapter, the suggestion is that the framework should exemplify software which illustrates how background science can be scaffolded as students construct explanations. This would illustrate aspects of the underlying task model for developing explanations, and should make this explicit rather than relying on the components of the task being implied by the framework.

The discussion of Guideline 4 developed the idea of scaffolding through activity spaces. It suggested that the tutorial's multiple choice questions represent a scaffolded heuristic for developing explanations. The data suggest that partially completed activity spaces can scaffold authentic tasks as students are apprenticed in the domain. Testing the affordances of the Quintana *et al.* (2004) guidelines in suggesting refinements to the design of activity spaces found that the guidance for designers on how to develop the task models which underpin activity spaces was lacking in detail. The granularity of the activity spaces relies on the granularity of the task decomposition that leads design of scaffolding. Again, annotations alongside exemplar software tools should explicitly articulate the process of developing scaffolding to support apprenticeship learning through partially completed activity spaces.

The discussion in this chapter also suggested that annotations should refer to literature which illuminates how particular scaffolding approaches sit within broader pedagogic approaches to science inquiry learning. Quintana *et al.* (*ibid*) make assumptions about designers' knowledge of the appropriate pedagogies and content of the domain. More explicit guidance of how the guidelines could be interpreted in the context of pedagogic content knowledge would allow designers to transfer scaffolding approaches to other contexts.

Although the conclusions from the study have drawn on literature outside the framework, the framework succeeded in providing a model for how to go about a principled analysis of scaffolding using empirical data. The framework is flexible enough for designers to apply it

to further examples of software, and could serve as a trigger to accessing further supporting literature in the way that has been exemplified in this study. The outcomes of using data to test the framework have led to the conclusion that its utility includes guiding iterative design of software, to include cycles of collecting empirical data from pilot studies, analysis according to the methodology used in this study and revisions. Specifically, testing the guidelines in the framework against empirical data has been shown to illuminate the scaffolding present in the *Acetabularia* tutorial and to identify gaps in the scaffolding.

The arguments in this chapter support the conclusion that, while individual guidelines in the Quintana *et al.* (2004) framework provide strategies for scaffolding some aspects of learning through inquiry, more detailed guidance is needed on the specifics of inquiry tasks and on how to structure the learning as part of a holistic learning experience. Setting up the inquiry to lead learning towards the development of explanations requires an overview of the whole activity, in addition to attention to the detail of individual tasks, sub-tasks and the media used to communicate these. Designers should be able to specify how the background science context is introduced in a way that frames the inquiry, how background science ideas are to be recruited and applied to develop reusable principles in science, and how students will develop reusable knowledge and skills through metacognition of the processes of inquiry which lead to these overarching principles. These broader pedagogic approaches and detail of the content of learning are as important for design as the consideration of scaffolding approaches.

Explanations in professional science are largely developed through discussion and persuasion. An additional inference from this chapter is that the role of software tools may be limited in their utility in transforming classroom discourse in a way that supports this process (Sandoval, 2003). The implication here is that the role of unfolding the stories of science across a teaching sequence may necessarily fall to the teacher. A software tutorial would then be seen as one of a sequence of activities which needs the expert teachers' skills to link the sequence of learning activities in a way that builds the big stories in science (Leach and Scott, 2002) and develops skills for science inquiry. Even so, in the context of large classes, with students representing a range of needs, the greater support that software tutorials can provide, the more the teacher is freed to pay attention to individual students' needs.

Chapter 6 Inferences from the study

6.1 The knowledge of designers

6.1.1 Inferences suggesting revisions to the framework

This study has used the Quintana *et al.* (2004) framework to analyse the *Acetabularia* tutorial, and tested the framework using empirical data from students using the tutorial.

This chapter discusses the implications from the study in terms of the design process, revisions to the *Acetabularia* tutorial and refinements to the framework.

The chapter explores how guidance in the framework needs to fit alongside other design considerations involved in developing educational software. In order to move forward to the next stage of revising the *Acetabularia* tutorial, by implementing changes suggested in this study, relevant guidelines in the Quintana *et al.* (*ibid*) framework are considered along with recommendations for additional guidance to support this process.

The student data showed a good fit with some of the scaffolding guidelines in the Quintana *et al.* (*ibid*) framework. But, this study suggests that the design challenge of revising the SNAB tutorial can't be addressed following the existing Quintana *et al.* (*ibid*) scaffolding design guidelines alone. The discussions in the previous chapter concluded that constructing explanations needs careful scaffolding beyond the scope of the framework's strategies. The relevant background science concepts and models in need of scaffolding must be integrated with the inquiry processes involved in developing explanations in a way that is not explained in the framework, and the pedagogical approach to this content needs to be made more explicit.

6.1.2 The pedagogic underpinning of design

The scaffolding guidelines in the Quintana *et al.* (2004) framework represent a position on the pedagogy of science inquiry learning. This position is grounded in theories on the nature of inquiry learning and pedagogical support for learners. Science inquiry learning is defined in the framework from a synthesis of the relevant literature, expressed in terms of the processes and cognitive tasks that students need to carry out.

Due to the generic nature of the framework, Quintana *et al.*'s (*ibid*) discussion of approaches such as cognitive apprenticeship (Brown, Collins and Duguid, 1989) and tasks

which keep learners in their zone of proximal development (Vygotsky, 1978) excludes detailed discussion of the pedagogies associated with transforming specific background science content for learning.

Educational design must be grounded in both sound pedagogic and content expertise, which parallels the expertise of an effective teacher. The scaffolding guidance in the framework makes assumptions about designers' expertise in the content to be scaffolded and their understanding of how this is most effectively transformed for learners. These assumptions apply to both background science concepts such as 'development' and 'protein synthesis' and procedural knowledge such as the structure of a scientific explanation. The framework's guidance also assumes that designers are clear about the specific role of scaffolding approaches in the wider design processes involved in developing an educational resource.

This chapter describes the challenge of applying the Quintana *et al.* (2004) scaffolding design framework to support explanations drawing on explanatory background science. The evidence for the importance of this issue comes from observations that SNAB students could make simple inferences from the observations of Hammerling's experiments made during the tutorial, but could not draw on prior knowledge to propose causal mechanisms for their observations. Students had been taught the relevant background science to illuminate this inquiry in the previous SNAB topic.

To support students in developing explanations, this chapter proposes that the designer needs to engage:

- expert procedural knowledge of the domain
- expert knowledge of relevant scientific concepts
- professional pedagogical knowledge of how to transform this procedural and conceptual knowledge for students
- professional design knowledge of how software tools can support learning.

The following discussion is organised by the aspects of professional design knowledge bulleted above. The next section discusses the science domain knowledge involved in science inquiry learning, and goes on to consider the pedagogic and design knowledge which the Quintana *et al.* (*ibid*) framework seeks to guide. Later sections discuss how scaffolding design should be integrated as part of the broader range of considerations that contribute to educational software design. Some revisions to the tutorial are suggested with

reference to this more holistic approach, and an interface for collecting and communicating the complex annotations and examples that form the body of educational design knowledge is suggested.

6.2 Expert procedural knowledge of the discipline

6.2.1 The uncertainty around a task model for explanations

Quintana *et al.*'s (2004) scaffolding design framework is organised around a task model of learning through science inquiry, within the overarching definition of 'posing questions and investigating them with empirical data, either through direct manipulation of variables via experiments or by constructing comparisons using existing data sets' (Quintana *et al.*, 2004, p. 341). While it defines the scaffolding design guidance through pedagogy (inquiry learning approaches) rather than the epistemology of the discipline (the processes followed by professional scientists) the framework does not succeed in every aspect of separating these two domains, nor do the authors argue why these should or should not be separated.

Quintana *et al.* (*ibid*) suggest that science inquiry learning is representative of ambitious learning. Science inquiry learning, as represented in the framework, de-emphasises the view of science as building, testing and revising models which has emerged from studies of contemporary scientific work (Nersessian, 2005; Duschl and Grandy, 2008; Windschitl, Thompson and Braaten, 2008). Testing the framework against empirical data has identified a flawed epistemological view of the discipline, where this has become confused with pedagogic approaches. For example, there is an assumption that explanatory theories will emerge if processes of inquiry are sufficiently scaffolded for learners.

In the past, science teachers have all too often used an underpinning epistemology of science based on a narrow view of 'the scientific method'. This is explicit in science text books and curriculum materials with only minor variations. It involves the processes of observing, developing a question, developing a hypothesis, conducting an experiment, analyzing data, stating conclusions and generating new questions. Windschitl *et al.* (2008) argue that this view of the scientific method, involving a faith in unproblematic procedural processes, is not scientific at all, and that it risks subverting learners' understandings of both the practices and the content of the discipline.

Chapter 2 set out the idea that explanations are products of science (see Section 2.5.1). Quintana *et al.* (2004) also acknowledge explanations as epistemic products that need to be

articulated in Scaffolding Strategy 7d: 'Highlight epistemic features of scientific practices and products' (p. 373).

While Quintana *et al.* (*ibid*) describe the need to consider the epistemic features of an explanation, they exemplify this idea with a tool that provides scaffolding as students link their explanations to evidence. Neither this example nor the framework in general consider the role of authoritative expositions of background science (Mortimer and Scott, 2003) where the focus for learning is an idea which students will not come to without expert input.

This study has found that, as part of the design process, a heuristic for constructing scientific explanations should be made explicit and that this heuristic should frame activities during inquiry learning. Developing explanations as part of science inquiry learning should refer to predictive and explanatory scientific models. In this way, data is clearly separated from the explanation, and the process of using a model to suggest causal mechanisms for the data is made explicit.

As discussed in the last chapter, the framework defines the broad areas of processes involved in science inquiry learning, but leaves the decomposition of sub-task models to the designer. Examples of software in the framework show how some specific interpretations of tasks and their sub-tasks have been approached but there is little commentary on this design process to help future designers. This lack of detail in the framework is one of the potentials barrier to applying the scaffolding guidelines to support construction of explanations. Generic guidelines for scaffolding approaches can only be applied if the designer has a clear model for the sub-tasks involved in constructing explanations. The sub-tasks define what needs to be scaffolded.

It is, though, difficult to define the content that needs to be scaffolded when the vocabulary to describe it is not agreed. The science which provides causal mechanisms that explain data might be called models, principles, theories or laws. The difference between laws, theories, models, ideas, concepts, facts, hypotheses and explanations is not well articulated. Science education literature points out the complex nature of defining what a scientific explanation is (Gilbert, Boulter and Rutherford, 2000; Sandoval, 2003; Millar, 2004). From the point of view of all the stakeholders in science education, including teachers, students, designers and examiners, the lack of clarity over the task model involved in constructing science explanations is illustrated by this confusion over the vocabulary frequently used for different forms of science explanations. The Quintana *et al.* (2004) framework could

provide annotations attached to examples of scaffolding, referring to a range of interpretations of task models for scientific processes linked to software examples in the framework. These designers' task models could contribute to the development of agreed task models within the science education community, as the process of educational design reveals the necessary decomposition of tasks for learners.

6.3 The need for expert knowledge of science content

In section 5.5.1, Ogborn *et al.*'s (1996) description of explanations as nested entities was discussed, and explanations were described as 'epistemic products of science'. Scientific explanations in the tutorial based on Hammerling's inquiry take various roles. These include the overarching explanation of how a cell develops; explanations of the protagonists which act, including *Acetabularia*, cells and cell parts; and explanations which provide the detail of causal mechanisms, such as protein synthesis and cell trafficking. The description of these roles suggests three ways that different types of explanation are situated within a specific scientific inquiry. Designers need a sense of which explanations need to be developed at each stage in an inquiry.

The Quintana *et al.* (2004) framework does not provide guidance on how to establish the protagonists which act in an inquiry. There are examples of software tools which decompose the process of producing explanations. For example, the '*Mildred*' guide in the *KIE* software (Davis and Linn, 2000) provides activity spaces for stages in the inquiry, with prompts for what students should be thinking and writing at each stage. The *WISE* environment (Linn and Slotta, 2000) provides similar support. Provision of activity spaces still assumes students' schemas for the entities which comprise scientific explanations are robust and can be resituated to a new context.

As it stands, the *Acetabularia* tutorial reflects an approach frequently used in school practical inquiry, where students find out *that* something happens, but do not link this with the causal mechanisms which explain what they observe. Establishing the models which provide these causal mechanisms needs to take place in parallel with the inquiry.

Chapter 5 suggested that an outcome of science inquiry learning should be that students' existing explanations are broadened to include new phenomena. For example, the concept of development is illustrated in previous SNAB topics by the change from a human zygote into an embryo. As a result of students' engagement with Hammerling's experiments 'development' should be broadened to include the detail of processes in individual cells.

'Protein synthesis' should become linked with how the nucleus controls development of specialised parts of single cells, broadening from the previous narrow explanation available to students associated with the function of the genetic code in determining the production of specific proteins.

Explanations are what frame each stage of an inquiry. It is not helpful to think of explanations as a single product which emerges at the end of the process. At each stage of an inquiry, students should be considering how well a particular explanation predicts how phenomena should behave, or how well the data fit the predictions leading from an explanation. Scientific inquiries are part of a complex way of accumulating, using and refining knowledge. Scientific explanations are as integral to inquiries as the data which validates them, and as such do not exist in isolation from the scientific process.

Students' views of explanations may be affected by the fact that these are the main area of content to be tested in assessment of the science curriculum. This results in explanations being seen as free-standing facts to be learnt off by heart rather than as the best tools we have to date to explain a range of observed phenomena. The Quintana *et al.* (2004) framework should be revised to include explicit guidance for how explanations can be validated and justified through scientific inquiry. In this way, learners would be introduced to explanations as a product of scientific inquiry.

6.4 Professional pedagogical knowledge

The language used to describe knowledge that teachers apply in a classroom situation acknowledges the closely intertwined elements of subject content and pedagogy. Teachers build up a repertoire of teaching models, analogies and illustrations which form their body of science as taught to students. This is often referred to as pedagogic content knowledge (PCK) (Shulman, 1986). Other authors have proposed additional areas as part of this professional knowledge base, including teachers' general education (Tamir, 1991) and emotional aspects of their work (Hargreaves, 1998). Even focussing narrowly on the intellectual rather than cultural aspects of a teacher's work, there is little consensus about the meaning of PCK (Corrigan, Gunstone and Dillon, 2011).

An expert teacher may be able to show how an area of science such as atomic theory can be explained, and how a sequence of activities builds up the story of science. Although mostly this process will be implicit rather than overt, teachers apply a task model of the cognitive processes which learners need to do carry out. They apply models of learning and

theories of learning to the specific domain content being covered. However, if the content knowledge of the learning (CK) is unclear, developing the task model of cognitive processes to be scaffolded, PCK, will be difficult.

The task model for developing explanations, and the way relevant teaching and learning approaches are applied to this task model have not been clearly articulated in previous studies. Relevant pedagogies come from work on argumentation, which provides an approach to knowledge construction through collaborative reasoning (Newton, Driver and Osborne, 2001) and cognitive acceleration, which emphasises thinking rather than 'doing' (King's College London, 2008). These studies have led to classroom resources that promote potential approaches to the cognitive tasks involved in constructing explanations. These existing resources do not suggest a single heuristic for developing an explanation any more than philosophers of science agree on a single 'scientific method' (Selley, 1989). The lack of agreement about the task models for inquiry processes only exacerbates the challenge for designers who wish to scaffold learning in this domain.

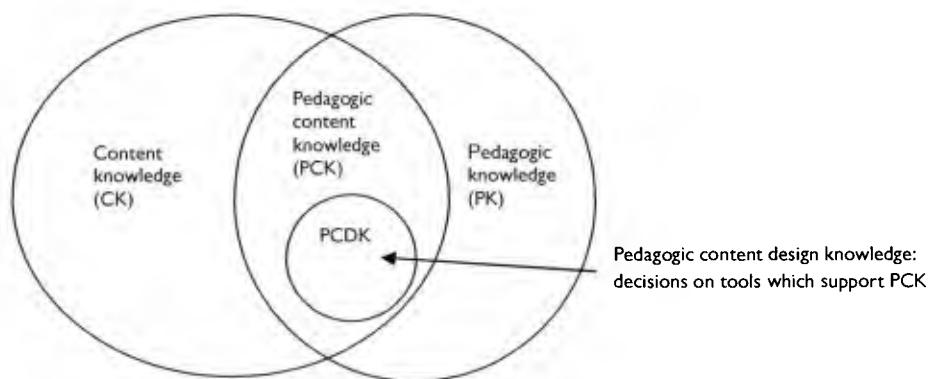
6.5 Professional design knowledge

6.5.1 Craft knowledge of the discipline

One of the conclusions from this thesis is that an educational designer's craft knowledge builds on the pedagogic content knowledge (PCK) of a teacher. By providing software examples, along with a commentary on how tools relate to specific pedagogical approaches, Quintana *et al.*'s (2004) scaffolding design framework illustrates how PCK is enacted in a particular medium or situation, and how it leads to decisions on appropriate tools and resources.

It might be appropriate to refer to an educational designer's knowledge as PCDK (pedagogic content design knowledge) (Figure 6.1). PCDK describes the application of PCK, where designers identify the most effective ways to support the pedagogies being applied to particular content. (Some teachers may, of course, develop this area of knowledge through their own practice.)

Figure 6.1 Pedagogic content design knowledge



The following sections suggest how the guidance from Quintana *et al.*'s (2004) framework needs to be integrated with other design, pedagogical and content specific considerations when developing educational resources. Later in the chapter, a suggestion is made for presenting the complex knowledge and guidance involved in educational design.

6.5.2 PCDK of explanations

In this study of the *Acetabularia* tutorial, three elements of the PCDK are identified as problematic. Firstly, the design of the tutorial is not underpinned by an appropriate model of how scientific explanations are constructed. As a result of this content knowledge (CK) being unclear, the transfer of content knowledge to curriculum content for science education (the PCK) is problematic. The result evidenced in the tutorial is a lack of an effective pedagogical approach to supporting students as they develop explanations as part of learning through science inquiry. Confusion between the epistemology of the discipline and the suitable teaching approaches for learners exists. The tutorial assumes that students will make links between observations from the Hammerling experiments and their knowledge from prior learning which explains these phenomena through much the same processes that professional scientists use to develop explanations from their inquiries. Finally, the translation of the pedagogic content knowledge into the design of tools (the PCDK) is flawed in the current tutorial as a result of the constituent CK and PCK being in question. For example, the tools which support the development of explanations do not scaffold students sufficiently to support links with background science ideas.

A pedagogic approach based on robust content knowledge lies at the heart of the translation of PCK into PCDK for explanations. This study suggests that design for science education is confounded by lack of clarity in the definitions of content knowledge of the

domain. The next section proposes an approach to PCK and PCDK based on the European tradition of Didaktik.

6.6 Didaktik as a model for PCK

The Quintana *et al.* (2004) framework reflects a trend in science education derived from the Anglo-American tradition of curriculum development. Within this tradition, decisions about the content of the curriculum take place largely independently of the practitioners who deliver it. The 'curriculum as manual' approach focuses on templates which guide day to day classroom practice (Westbury, 2000). Fischler (2011) suggests two other factors affecting this marginalisation of practitioners in the selection of curriculum content. He points to the recent emphasis on cognitive psychology in research into teaching and learning which backgrounds the importance of what is being taught. He also suggests that the influence of large scale international studies leads to standardisation of educational goals across countries. Teachers played an increasingly minor role in the design of curriculum content.

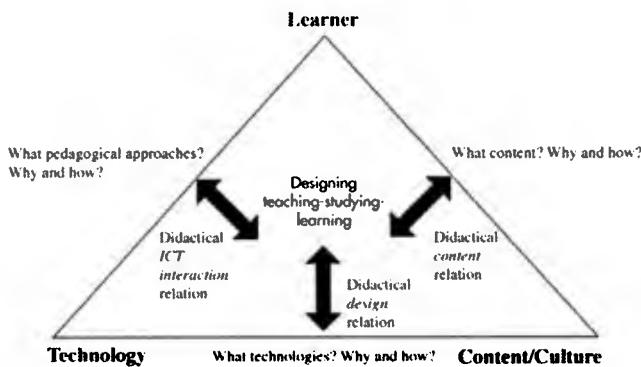
Curriculum development with the aim of improving science education must relate to both choice of content and the way this content is translated for instruction, taking into account students' cognitive and social dispositions and preconditions. While the Anglo-American tradition takes a technical view of curriculum, emphasising content and teaching schemes, the German tradition of Didaktik emphasises instruction, or 'the art of teaching' (Kansanen, 2009).

One of the problems identified in the scaffolding analysis of the *Acetabularia* tutorial is that the role of the tutorial in developing specific background science concepts is not clear. The Quintana *et al.* (2004) framework does not provide strategies to move the design of the tutorial forward in this respect, because there is an implicit assumption in the guidance that inquiry learning will lead to science explanations as long as the inquiry process is adequately scaffolded.

Didaktik potentially provides the intellectual framework to support the link between subject content and pedagogy that has been identified as problematic in this study. It acknowledges the professional role of teachers (and designers) in interpreting the statutory curriculum. It avoids the gap in Anglo-American traditions between curriculum and what actually happens in the classroom (Westbury, 2000).

Hudson (2008) proposes a model for technologically-supported learning based on a Didaktik approach (Figure 6.2). Hudson models learning activity from a teacher perspective, but this could equally apply to a designer perspective, the endpoint in both cases is learner activity. The model shows the relationship between PCK and PCDK that is missing from Quintana *et al.*'s (2004) framework. PCDK is shown in the model as the interface between content, pedagogical approaches and tools.

Figure 6.2 Hudson's (2008) didactical model for technology-supported learning



The Quintana *et al.* (2004) framework organises its guidance according to scaffolding approaches which underpin the interaction between ICT tools and students. The software tools in the framework provide examples of didactical ICT relationships, in the interaction between pedagogic approaches (scaffolding) and ICT tools. The framework answers the question 'what technologies, why and how?' in relation to specific scaffolding approaches.

Missing from the framework is guidance on the interaction between educator, learner and content which gives rise to decisions about what content should be taught and how it should be taught. This substance of Didaktik is not a common feature of science education literature in the Anglo-American tradition. Didaktik presents a potential solution to the need for more guidance on how to move from specific content (a science topic) to PCDK (the tools which support a particular approach to learning the topic). The Quintana *et al.* (*ibid*) framework guides the instructional approaches for scaffolding, but does not position this single element of PCDK in the wider design process. Specifically, the framework does not make the underpinning content and broader pedagogic approaches explicit. Neither does it guide the choice of specific technologies.

Didaktik emphasises how content of a domain is structured for learners before it is considered in relation to generic pedagogic approaches. This approach foregrounds domain

content as being at the centre of pedagogy, while acknowledging the social, emotional and philosophical aspects of learning (Klafki, 2000). It could be argued that, by identifying the three elements of inquiry learning (sense making, process management and articulation and reflection) and by defining scaffolding approaches relevant to these, Quintana *et al.* (2004) have carried out the necessary Didaktik analysis to guide the support of learning. But, if one purpose of the inquiry is to develop background science concepts, then 'inquiry' becomes an approach to learning that particular content. Here lies the source of confusion which has been articulated in the literature on science practical work (Abrahams and Millar, 2008). The assumption that inquiry represents a suitable pedagogy for the Didaktik of science concepts is problematic: for designers, there is confusion about whether science inquiry is a pedagogic approach, or whether it forms the content to be learnt. Without the separate Didaktik analysis of the background science content which frames an inquiry, the design of scaffolding for science inquiry is isolated from the full context of the content which informs decisions about pedagogic approaches. The resulting designs, as exemplified in the Quintana *et al.* (2004) framework, do not address the need to integrate scientific processes and background science, as the emphasis is on learning science inquiry processes.

This study of the *Acetabularia* tutorial emphasises the need to balance experiential approaches with guided instruction that builds on students' intuitive thinking. The study also highlights the need for more detailed guidance on approaches to individual inquiry tasks and approaches to integrating background science.

The discussion in Chapter 2 around the effectiveness of inquiry-based and problem-based learning raised the need to consider complex learning in terms of the support and guidance needed to make it work (Kirschner, Sweller and Clark, 2006; Hmelo-Silver, Duncan and Chinn, 2007). The Hudson (2008) model shows designers how their work sits at the interface between content, pedagogy and software tools in the design of scaffolding tools for science inquiry.

6.6.1 A Didaktik analysis of the Quintana *et al.* framework

The software tools exemplified in the Quintana *et al.* (2004) framework are restricted to the pedagogic approach of scaffolding, and to the content of science inquiry processes.

What technologies? and Why?

‘What technologies?’ in the Hudson didactical⁹ (2008) model refers to the range of technologies available for educational purposes. Understanding which technologies are potentially applicable in an educational design context is a component of design knowledge (DK). Technologies can then be applied to teaching approaches. Pedagogic approaches to science inquiry learning (PK) are described in Quintana *et al.*’s (2004) guidelines, forming the scaffolding design categories of sense making, process management and encouraging articulation and reflection. This approach to PK is identified from the extensive literature on science inquiry learning, and answers ‘What pedagogies?’ ‘Why?’ and ‘How?’ on the left hand side of the Hudson (2008) model.

‘What technologies?’ is implied by the list of scaffolding tools described in the Quintana *et al.* (2004) framework but the DK underpinning choice of technologies is not discussed as a separate element. For example, a justification for using video might be that video presents life-like sequences of images to represent events over time. Hyperlinking could be chosen as a technology which allows interactive, non-linear navigation between assets.

‘Why?’ raises the aspect of pedagogic design knowledge (PDK) which justifies use of technologies. For example, the pedagogic affordances (PDK) of hyperlinking may include the idea that expert guidance can be provided as an optional, additional asset in a tutorial without changing the linear narrative of a task. The pedagogic affordance of video might include the functionality to stop, start and replay, allowing students to analyse a process which happens over time. The scaffolding strategies in the Quintana *et al.* (*ibid*) framework represent PDK because they combine DK and PK to suggest how technologies can support a particular pedagogic approach, even if the detail of the DK and PK is sparse. For example, in the description of *Thinker Tools* software (White, 1984) under Guideline 1, the framework draws attention to a pedagogic approach which aims to convey the notion of acceleration. Students explore moving objects which leave a visual trail of equally timed marks. The technology involved here is simulations of moving objects which leave trails, and which learners can explore.

PDK in the framework’s strategies is generalised for all aspects of science inquiry, but how it can be applied to specific inquiry processes is exemplified through the software in the

⁹ Hudson uses the English spelling ‘didactic’, so references to his model use this spelling. Elsewhere, the European spelling ‘Didaktik’ is used to distinguish this approach from the common English interpretation relating to teacher-led learning.

framework. The task of transferring knowledge of the functionality of a specific technology (DK) to an educational application can be represented as (DK + PK → PDK). The PDK of designers is assumed in the framework and the processes involved in design are not explicit enough to support novices to this discipline.

How?

How specific technologies are utilised in a particular educational context is also an element of PDK, and is answered in the Quintana *et al.* (2004) framework by the software which is exemplified.

What content? Why and How?

Science inquiry processes are described in general terms in Quintana *et al.*'s (*ibid*) discussion of the framework, but are not presented as a task model with the level of detail needed for designers. Background science concepts are also referred to, but as contexts for the processes being scaffolded rather than the focus of scaffolding. The recommendations from this study include the need for a Didaktik analysis of inquiry processes, pedagogies and suitable technologies for science inquiry learning. The Didaktik model underpinning design in the software examples needs to be made explicit, and should include guidance on how scaffolding strategies can be applied to background science.

Quintana *et al.*'s Didaktik model of scaffolding design

The epistemological approach of the Quintana *et al.* (2004) framework reflects the lack of distinction in science education between the content and processes of the discipline and the pedagogies which are suitable for teaching this content. Science inquiry processes are treated as content in the framework and, as such, are discussed as entities to be scaffolded as students carry them out and learn about them. The scaffolding approaches in the framework relate to this 'science inquiry learning' content.

As discussed earlier, science inquiry is also acting as a pedagogical approach for learning the background science ideas, such as 'development'. Using Hudson's (2008) model (Figure 6.2, p.188), both 'scaffolding' and 'inquiry' should be on the left hand side of the triangle, as pedagogical approaches. Background science and science inquiry processes form the content referred to on the right hand side of the triangle.

It is not always possible to distinguish pedagogic content knowledge (PCK) from pedagogy or from knowledge (Kansanen, 2009). PCK comprises practical knowledge of teaching

approaches and the knowledge that the teacher wishes to mediate to students. In the case of inquiry, the teaching approach and content to be mediated may overlap. How to scaffold learning is, on the other hand, pedagogical knowledge which the teacher has, but which is not to be transferred to the student.

The Didaktik analysis of scaffolding design for inquiry is suggested as a way to tease out and articulate the elements of PCDK that are involved in a way that allows this applied knowledge to be discussed by the design community.

The critique of the Quintana *et al.* (2004) framework in this study identified insufficient guidance in the CK and PCK of learning through science inquiry. The next section exemplifies the process of Didaktik design suggested by this study. It sets out some suggested revisions to the *Acetabularia* tutorial which emerge from an analysis of constructing explanations, and which integrates processes and conceptual content of science.

6.7 Revising the framework for design

6.7.1 A summary of the revisions to the tutorial and framework

This study showed that students do not make links between development in *Acetabularia* and prior knowledge of protein synthesis. The evidence suggests that *Acetabularia* needs to be established as a single cell, and distinguished from multicellular plants and single cells that are part of multicellular organisms (see data in Section 4.2.2). Models which offer causal mechanisms for the observations in the experiments on *Acetabularia* should also be established in a way that makes the relevant nested science knowledge and understanding explicit (Ogborn *et al.*, 1996). Development in a single cell, leading to specialised structures, needs to be distinguished from development of tissues and organs in multicellular organisms.

Making links between evidence and explanatory theories is a challenge for inexpert students. The Didaktic approach to building explanations through inquiry might involve the designer in providing access to the relevant theories in a way that still gives students a meaningful learning task, but acknowledges that theory does not emerge unproblematically from data (Millar and Abrahams, 2009).

In summary, the data and the literature review from this study suggest the following revisions to the Quintana *et al.* (2004) framework:

- The guidelines should be considered in the context of a more holistic view of design, including explicit commentary on pedagogy, and the affordances of technology in relation to specific content (see Section 5.6).
- The guidelines should be applied to and exemplify scaffolding of background science in addition to science inquiry processes (see Section 5.3).
- The framework should be based on a more authentic view of the scientific method, where evidence and explanations are seen as discrete elements of developing scientific knowledge (see Section 5.4.2).
- Examples of and annotations on the work designers must do to apply the guidelines in a specific context should be provided. For example, the development of detailed descriptions of the PCDK involved in specific designs and its constituent elements (including detailed task models) (see Section 6.5.2).
- Case studies and annotations from designers should refer to additional literature which has informed design decisions (see Section 5.6).

The study also suggests the following revisions to the *Acetabularia* tutorial, expressed below as generic notes which could annotate a revised version of this tutorial in the framework:

- Expositions of potential explanatory scientific models should be provided to students for critique in an inquiry rather than expecting students to infer these for themselves or to resituate models from prior learning (see Section 5.5.1).
- The entities which act in the inquiry should be established more effectively (see Section 5.3.1).
- Where appropriate, students should be primed for learning by suggesting their own explanations before testing and reflecting on their suggested models (see Section 5.5.1).
- Hints, guidance and feedback should support learning, to avoid guessing and resorting to test-clicking to find solutions (see Section 5.5.1).
- Extraneous cognitive load should be reduced and germane cognitive load maximised (see Section 5.4.2).

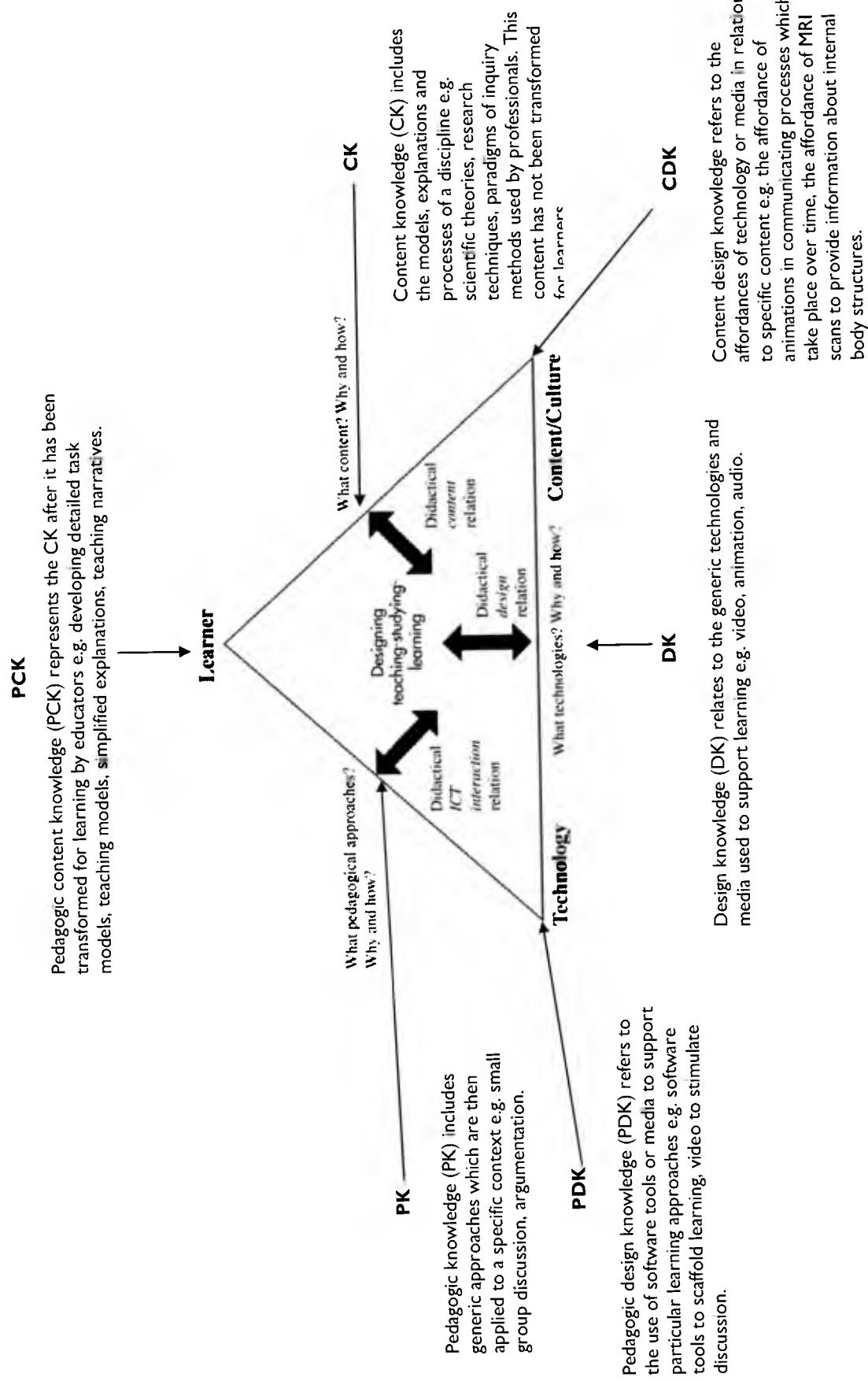
6.7.2 A holistic didactical framework for design

Figure 6.3 shows a generalised adaptation of Hudson's (2008) didactical model, annotated with a description of the elements of PCDK.

The following sections apply the adapted Hudson design framework in the context of revisions to the *Acetabularia* tutorial. This more holistic, adapted version of the Hudson (2008) didactical model has been integrated with the Quintana *et al.* (2004) scaffolding design framework to show how scaffolding design contributes to pedagogic design

knowledge (PDK). The new model also integrates a task model for the background science content involved in explaining development in *Acetabularia*, representing a more detailed re-work of the original task model (see Section 3.2). In addition, it integrates a task model for science inquiry based on the paradigm of model-based inquiry (Windschitl, Thompson and Braaten, 2008).

Figure 6.3 An adaptation of the Hudson (2008) didactical model showing the elements of PCDK



6.8 Didactical designs for the revisions

6.8.1 Applying the didactical framework to revisions of the tutorial

The generalised didactical model for PCDK (Figure 6.3) is now developed in a specific context, by defining the elements of PCDK pertaining to the revisions to the *Acetabularia* tutorial. The science content (CK) is based on a revised version of the task model for the tutorial, with refinements suggested by this study. For example, the science needed to explain development at the level of causal mechanisms has been added to the original version used in the analysis (see Section 3.2). The scientific processes in the original task model have been revised to reflect the model-based inquiry paradigm, where a scientific model frames predictions and explanations of the data. The process of unpacking the detailed task models for scientific concepts and processes reflects the Didaktik tradition of curriculum development which emphasises the transformation of content.

CK

The content knowledge of the tutorial includes the science inquiry processes, along with background and contextual science concepts involved in explaining the Hammerling experiments:

- The nucleus of a eukaryotic cell contains the genetic code, made up of triplets of bases on the DNA molecule.
- Protein synthesis in the cytoplasm results from transcription and translation of the genetic code.
- Development in a cell involves specialisation of cell parts.
- Enzymes are globular proteins which act as catalysts in intracellular and extracellular reactions of living organisms.
- Molecules produced directly or indirectly by protein synthesis are modified in the endoplasmic reticulum, and transported through the cell in the Golgi apparatus and vesicles.

The following is the CK of science explanations associated with the model for the scientific method proposed by model-based inquiry:

- Tentative models which explain phenomena should lead to testable hypotheses which make sense within the context of a broader scientific model.
- Data should be collected systematically with the purpose of testing the model.
- Causal arguments should be constructed which attempt to validate patterns in the data, and which support or refute explanatory causal claims in the hypothesis based on the original model.

(Windschitl, Thompson and Braaten, 2008)

DK

Design knowledge includes knowledge of the functionality of the technologies used. As with CK, the DK is expressed in a way that might be used by a professional using technologies in any of a range of applications:

- Flash animation integrates graphic visuals, text, animations and video into seamless streamed series called 'Shock Wave' movies, which are suitable for web delivery. Flash uses up less bandwidth than corresponding visuals or movies in other formats.
- Hyperlinks are references within documents or other files that are activated by clicking. They take users to another location within the document or file, or out to external locations.
- Feedback provided within a learning technology allows an interactive transaction between the question, students' responses and feedback provided by a software programme.

PK

The following pedagogic ideas from the literature have been discussed earlier in terms of how they inform the PCK and PDK of the tutorial:

- Build on students' existing knowledge to construct the entities which act in the inquiry (Ogborn *et al.*, 1996).
- Provide support for students to develop differentiated knowledge structures (Schwartz and Bransford, 1998).
- Reduce extraneous cognitive load (Sweller and Chandler, 1994).
- Create an interest in the setting of the inquiry to create a gap which needs to be bridged with further understanding (Ogborn *et al.*, 1996).

- Stimulate students to articulate questions and problems which are involved in the context or applications of the science (Ogborn *et al.*, 1996).
- Create a 'time for telling' the explanatory scientific models (Schwartz and Bransford, 1998).
- Create tasks which lead to explanatory knowledge structures (Schwartz and Bransford, 1998).
- Rather than using inquiry to teach (or 'discover') scientific theories, students should critique theories which they are provided with against the data they collect (Sutton, 1992).
- Tasks should mirror the way scientists develop theories iteratively, for example through testing models (Windschitl, Thompson and Braaten, 2008).

Depending on the learning outcomes of an activity, inquiry processes may appear in both CK and PK. In the suggested revisions to the *Acetabularia* tutorial, the CK includes the processes involved in producing causal explanations. Where inquiry processes are within CK, the learning outcomes include metacognition of these processes on the part of the student. Where they appear in PK only, they are mechanisms for approaching other content to be learnt.

The following list of pedagogies represents the PK relevant to the *Acetabularia* tutorial based on Windschitl *et al.*'s (2008) suggestions for how model based inquiry could be applied in science inquiry learning:

- Investigation should emerge from a motivating interest in the natural world.
- The phenomena of interest, along with potential explanatory models, should be established through exposition.
- Opportunity should be provided for students to develop tentative models to explain phenomena.
- Students should generate testable hypotheses which make sense within the context of a broader scientific model.
- Data should be collected systematically with the purpose of testing the model.
- Causal arguments should be constructed which attempt to validate patterns in the data, and which support or refute explanatory causal claims in the hypothesis based on the original model.

PCK

The PCK includes the content from the specification for the SNAB course which is to be covered by the tutorial, contextualised by the teaching narrative of the Hammerling experiments. The PCK represents the CK after it has been transformed to make it accessible for learners:

- As a unicellular organism, *Acetabularia* is a specific example of a cell with specialised structures.
- *Acetabularia* is large enough that it can be manipulated to investigate which part of the cell controls development.
- *Acetabularia* can be dissected, cells parts rejoined and the nucleus transplanted to different parts of the cell. Whole cells or parts of the cell can be grown in a Petri dish.
- Scientific inquiry processes lead to the deduction that chemicals produced by the nucleus move into the cytoplasm and control development of the hat in *Acetabularia*.
- These controlling chemicals are proteins produced by transcription and translation of the genetic code in the nucleus.
- Enzymes which catalyse chemical reactions in cells and structural proteins are both involved in development.
- Development in *Acetabularia* is a specific example of the role of the nucleus in development which can be applied to other eukaryotic cells.

PDK

The following design solutions to pedagogic support for science inquiry are based on the Quintana et al. (2004) scaffolding design guidelines which were discussed in relation to the *Acetabularia* tutorial in Chapter 5 (Guidelines 1, 3, 4, 5 and 7). Whereas Quintana et al. (*ibid*) refer only to scaffolding scientific processes, a suggested revision to the tutorial is that these guidelines should be applied to background and contextual science content listed under PCK.

Software tools can scaffold learning through:

- Using representations and language that bridge with prior learning (Guideline 1)
- Using representations that learners can inspect to reveal important properties of underlying data (Guideline 3)

- Providing structure for complex tasks and functionality (Guideline 4)
- Embedding expert guidance about practices of the domain (Guideline 5)
- Facilitating ongoing articulation and reflection during learning (Guideline 7).

(Quintana *et al.*, 2004, p. 345)

CDK

The technology and media used in the tutorial to communicate specific content includes:

- Animations which communicate the processes of the Hammerling experiments.
- Formalised visuals which communicate specific structures using scientific conventions.
- Interactive feedback and support for the task of linking evidence and conclusions.
- Video which communicates life-like scenarios.
- Hyperlinks which allow non-linear navigation to a range of information and tools.

PCDK is the integrated product of the elements of content, pedagogy and design as they are applied in a specific context. This section has shown that it is possible to articulate PCDK for the design of revisions to the tutorial, framed by a didactical model combining Quintana *et al.* (2004) and Hudson (2008). The Quintana *et al.* (*ibid*) framework provides a rationale for the scaffolding approaches which are a single aspect of the pedagogical approaches used in the *Acetabularia* tutorial. This exercise of developing a combined didactical model illustrates how the Quintana *et al.* (*ibid*) framework must be positioned within a much broader set of design considerations. Scaffolding design needs to be considered along with the other elements of PCDK in an integrated, holistic design process.

The designs for some suggested revisions to the tutorial are now presented, focussing on two significant areas identified from this study: establishing the protagonists and designing within the model-based inquiry paradigm. The aim of these following sections is to show how design might be framed by a didactical model which considers all the elements of PCDK, and how this design process might be articulated.

6.8.2 Establishing the protagonists

An interest in the inquiry could be introduced by showing a video of *Acetabularia* in its natural environment. Students then suggest what type of organism it is, providing reasons for their categorisation. This primes them for the explanation of *Acetabularia* on the next screen, which provides an interactive diagram of the cell. Students can explore the organisms' structure through interactivity which leads them to descriptions of the structures relevant to the inquiry, and a glossary of the key terms used. The diagrams and descriptions of the structures and glossary are generalised rather than contextualised to *Acetabularia* where possible. For example, a rolling label for the nucleus and cytoplasm provides information on these cell components. Structures which are specific to *Acetabularia*, such as the rhizoid and hat, need more contextualised explanations.

The drive for students to explore *Acetabularia* as an entity is a comparison between their initial explanation of what it is after watching the video and their revised explanation. After watching the video, students are asked to articulate their explanation of *Acetabularia* in a notebook tool. The tool is also made available from the interactive diagram screen, so students make notes on their new explanation alongside the previous one, reflecting on how their model of *Acetabularia* has been revised.

The notebook tool is based on a simple text editor, and provides a structured set of activity spaces for articulation and reflection at each stage of the tutorial. For example, the notebook could contain questions which prompt students' written responses, and it could structure a comparison of students' initial predictive models with the revised models after each experiment. It could provide tabulation to organise tasks which need responses in several categories, such as the summative activity suggested after Experiment 4 (see p.207).

The notebook screen also provides links to expert hints and guidance which support the tasks, and to the background science explanations that students will need to draw on.

6.8.3 A model-based inquiry version of the experiments

The revised tutorial could use the Hammerling experiments to test and critique explanatory models for development in *Acetabularia*. The early experiments should model a heuristic for the new approach to inquiry which can be applied in the later tasks. This builds on the successful

strategy discussed in Chapter 5, where multiple choice questions in the tutorial were identified as providing activity spaces to develop evidence based conclusions. The tutorial should provide accounts of potential explanatory theories rather than relying on students accessing their prior learning.

Experiment 1

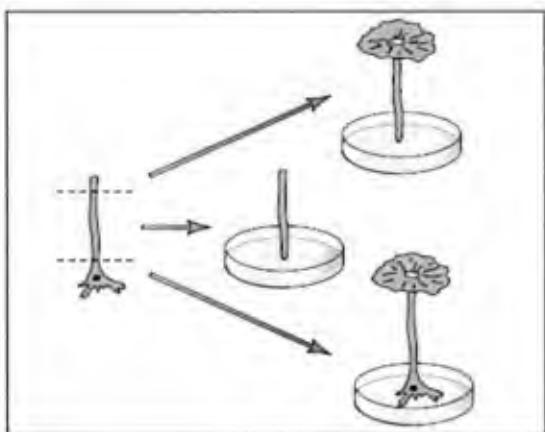


Figure 6.4 Summary of Hammerling's Experiment 1

In Hammerling's Experiment 1
Acetabularia was cut into three sections
which were allowed to develop separately

Having introduced *Acetabularia* on the introductory screens, the narrative for Experiment 1 (summarised in Figure 6.4) should introduce the idea that Hammerling realised that *Acetabularia* can be cut up, and that each individual section of the cell can be cultured in a Petri dish. The narrative should continue to explain that Hammerling suggested that development might be controlled by genetic (inherited) material, and that any part of the cell which contains this material should be able to develop into a complete cell.

Students could use the notebook tool to predict what might happen if the three separate sections of *Acetabularia* are grown, justifying their prediction using Hammerling's model which suggests that genetic material controls development.

The drag and drop simulation of Experiment 1 used in the current tutorial could be used for students to make observations from this experiment. Using the notepad, students then reflect on their initial model in relation to their observations from the experiment.

This suggested revision to Experiment 1 provides restricted activity spaces for the early stages in a model-based inquiry. The tasks are restricted by providing the inquiry question and the initial model on which students' predictions are based. Data collection is restricted through a set drag and drop animation with no scope for trying out different experiments.

Experiment 2

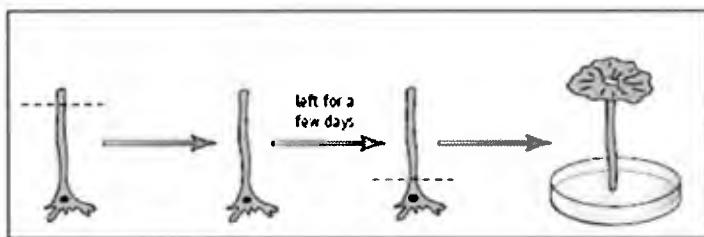


Figure 6.5 Summary of Hammerling's Experiment 2

In Experiment 2 the tip was cut off a young cell and the rhizoid was left attached for a few days. The rhizoid was then cut off and the stem

developed a hat.

The narrative for Experiment 2 (summarised in Figure 6.5) includes the idea that because only the rhizoid grew a complete cell in Experiment 1, Hammerling decided to test whether the genetic material is present in the both the tip and the rhizoid or the rhizoid alone. He based this experiment on a model that suggested the genetic material is in the rhizoid, and that the rhizoid controls development by sending chemical signals to the tip.

Students are then asked to predict what would happen if the tip is cut off, the rhizoid left attached for a few days and then the stem cut off to see how it develops.

Predicting the outcome of Experiment 2 based on Hammerling's model is followed by the drag and drop Experiment 2 from the original tutorial. Again, students reflect on the initial model in relation to the observations from the experiment using the notebook tool. The reflection is prompted by some questions and hints based on the multiple choice questions in the original tutorial.

The questions could include:

- The original model which framed Experiment 2 was 'the rhizoid contains the genetic material and sends chemical messages to the stem which allows the stem

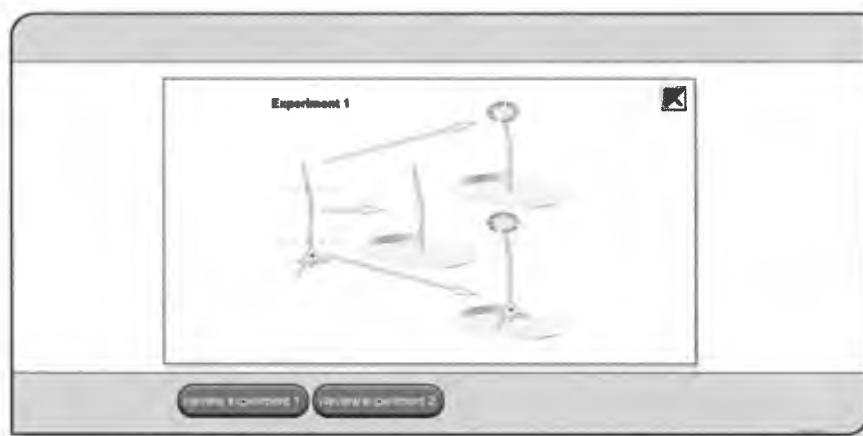
to develop a hat'. Reflect on the original model in light of the evidence from Experiments 1 and 2.

- Do the results of Experiment 2 support or refute this model?
- Do the results from Experiment 1 support or refute this model?
- What science explanations can you add which help to explain the results of Experiment 2?

These questions avoid the complex logic of the multiple choice questions in the original tutorial as evidence from just one experiment is considered at a time. The questions also prompt students to draw on other explanatory models from their prior learning but apply these in the new context. A series of brief summaries of potential explanatory theories are provided from a button in the navigation of this screen, and all following screens. These explanations are decontextualised, so students have to resituate them in the context of development in *Acetabularia*. The explanatory models provided should include the PCK 'background science ideas' listed above (see p. 199).

Hint buttons provide a pop-up summary of this experiment and the previous experiment to reduce the cognitive load involved in going back in the tutorial to review the full animations of these experiments (Figure 6.6).

Figure 6.6 Hint button summarising experiment 1



Hint buttons should also support students' interpretations of the experiments as they critique the initial explanatory model using the evidence from the experiments (Figure 6.7). This

approach avoids students guessing the answers to questions and provides additional scaffolding to move their thinking on if needed.

Figure 6.7 Hint box to support students' interpretation of Experiment 1



Experiment 3

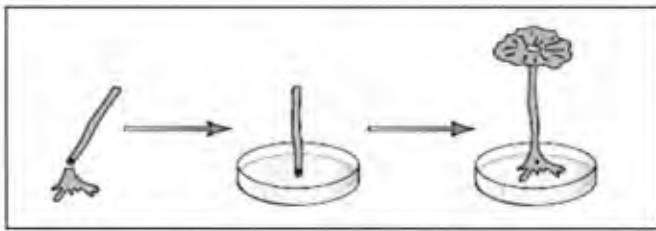


Figure 6.8 Summary of Hammerling's Experiment 3

In Hammerling's Experiment 3 the rhizoid and tip of a young *Acetabularia* were cut off. The nucleus was transferred from the rhizoid into the stem. The stem developed a complete cell with hat and rhizoid.

The introduction to the revised Experiment 3 sets out the idea that Hammerling needed to establish whether it is the nucleus or the rhizoid which controls development (Experiment 3 is summarised in Figure 6.8).

Revisions to the tutorial should prompt students to suggest a model which provides an explanation for either the nucleus or the rhizoid controlling development. This task is supported by background science explanations which are still available from a background science button.

Experiment 3 is then provided for students as a tool which allows more open manipulation and investigation of *Acetabularia*. In contrast to the restricted animations of the current tutorial, a workbench tool provides sufficient annotated guidance of the tools and techniques available for Experiment 3 to allow students to formulate a model based prediction and plan, followed by data collection to test their model (Figure 6.9). The rationale for designing this tool is based on data from students carrying out paper-based Question 6 in this study which showed that students applied techniques of the experiments successfully when planning their own experiment (see data in Section 4.2.3).

Data from Question 6 also suggested that engaging with the inquiry question as they produce their own plan may 'prime' students for engaging with Hammerling's version of the same experiment.

Figure 6.9 Workbench for Experiment 3 showing roll-over guidance on the pipette tool



Students' initial model and post-experiment reflections on their model are prompted by questions in the revised tutorial's notebook tool. Support for interpreting evidence from Experiment 3 and previous experiments are provided in the form of hints, as described for Experiment 2. By the end of this experiment the revised tutorial will have supported students to develop their own predictions based on their own explanatory models. Students will have planned and carried out a virtual experiment on a single *Acetabularia* using techniques of dissection, nuclear transplant and cell culture.

Experiment 4

Experiment 4 (summarised in Figure 6.10) requires careful revision to reflect the model based inquiry format, as the conclusion from the first stage of the experiment is not obvious. The revised tutorial provides a workbench (Figure 6.11) which allows students to plan and carry out an experiment to test whether the nucleus controls development, using two species of *Acetabularia*. This revision develops Question 6 in this study by allowing students to test their ideas and 'discover' that intermediate hats develop when the hats are cut off and the nucleus is transferred between species. The conclusion statement for this observation is provided in the revised version, and, as with the earlier experiments in the current tutorial, students are asked

to select evidence from the experiment which supports and refutes the conclusion provided. If needed, they can return to the workbench tool to test their conclusion.

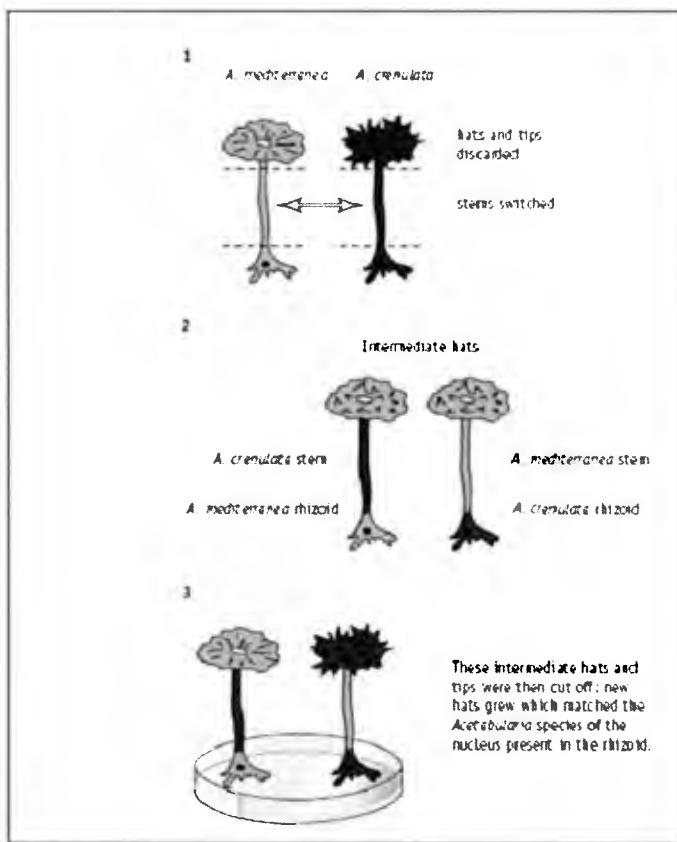
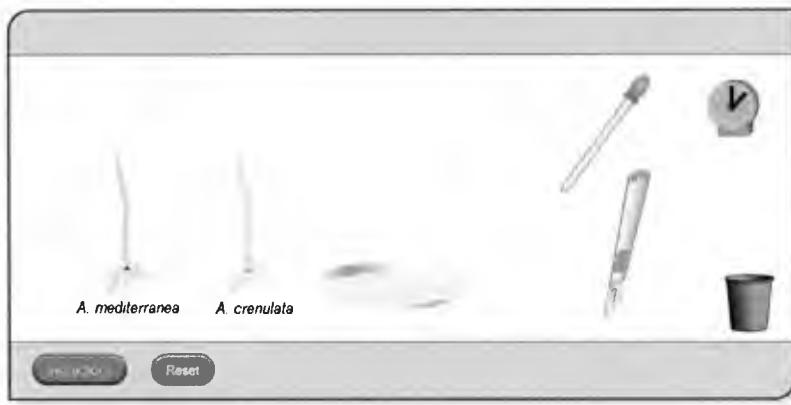


Figure 6.10 Summary of Hammerling's Experiment 4

In Experiment 4, Hammerling swapped the rhizoids and stems of two individuals from different species of *Acetabularia*. The stems developed hats which were intermediate between the two species. When these hats were removed, new hats grew which corresponded to the nucleus in the rhizoid.

Figure 6.11 Workbench for Experiment 4 with two species of *Acetabularia*



Having established that chemicals from the previous nucleus remained in the cytoplasm and influenced the development of the first hat, students are introduced to the idea that Hammerling cut off the intermediate hat to find out which type of hat regrows on the stem. They are prompted to produce a revised model and experiment plan for the second stage of the experiment. Hints and guidance would provide leading questions and suggestions to support students as they develop a second stage model or plan.

Building an increasingly complex set of overarching principles in science

Once students have refined their model of control of development in *Acetabularia*, using evidence from all four experiments and the background science explanations provided, they could carry out a summary activity based on Question 8 in this study. The aim of this task would be to consolidate learning from the tutorial, and to set the models for control of development into a broader context.

The tool could organise students' responses into three categories (Table 6.1).

Table 6.1 Summary activity for revised tutorial

Conclusions about control of development in <i>Acetabularia</i>	Evidence from experiments which supports these conclusions	Evidence from experiments which refutes these conclusions	Models which provide causal explanations for these conclusions

The heuristic for producing scientific explanations implied by the task in Table 6.1 relates to the Quintana *et al.* framework's (2004) implied heuristic for explanations based on Sandoval (2003). This is discussed in Chapter 5 in relation to strategy 4b. It builds on the heuristic underlying the multiple choice questions of the original tutorial discussed in relation to Guideline 4 (see data in Section 5.4.2) by separating the data, conclusions and causal mechanisms involved in scientific inquiry. Students are expected to resituate the generalised science explanations provided in the tutorial to support their model explaining development in *Acetabularia*.

The revised tutorial provides an increasingly less restricted set of tasks as students take part in some aspects of model based inquiry. The germane cognitive load is maximised through involving students in the planning and interpreting of the experiments. These tasks also involve students in the inquiry questions, so they appreciate the cell-biology-based context that can be investigated using *Acetabularia* as a proxy for eukaryotic cells. Scaffolding in the form of hints and expert guidance structures students' thinking, to keeps them engaged in the relevant cognitive tasks. The authentic practice of developing and testing scientific models is practised, with the support of relevant models which are provided rather than expecting students to discover these themselves, or to draw on them from prior learning. The cognitive task of resituating the models is involved in this revised tutorial, but is supported through the guidance and prompts in the questions.

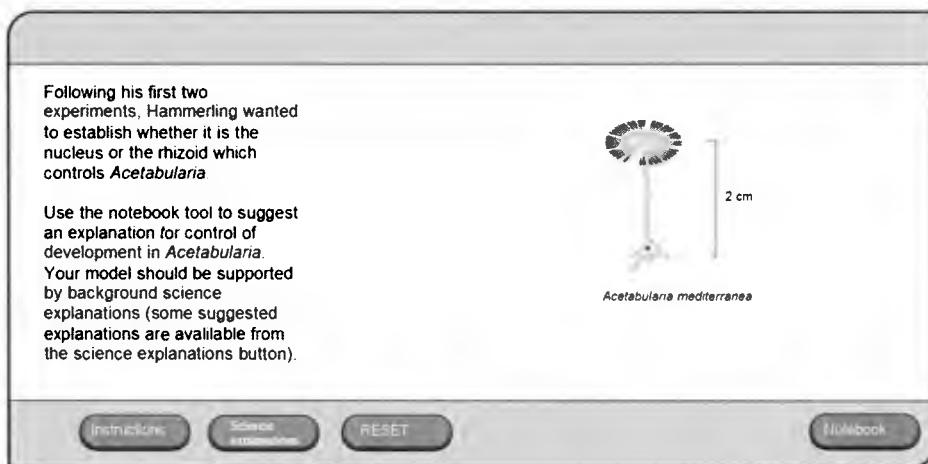
The tasks suggested in the revised tutorial could equally be applied to practical science inquiry. As such, the tutorial serves as a model of using inquiry to develop science understanding for teachers and students.

6.9 Presenting the PCDK

The remaining task in this study is to suggest how the PCDK of a design can be presented in a way that builds on the critique of the Quintana *et al.* framework (2004) in Chapter 5, including the suggestion that it should be embedded in a more holistic didactical model presented earlier in this chapter. The following section takes one of the suggested revisions to the tutorial, and presents this tool (see table 6.2) within a suggested PCDK framework using the revised didactical design model (Figure 6.3) based on Hudson (2008) and Quintana *et al.* (2004). This presentation of a didactical analysis of the PCDK of the revised Experiment 3 follows the design elements described in Section 6.8.1, which refers to the underpinning PK, CK and DK along with the PCDK of the entire resource.

Table 6.2 A model for presenting the PCDK exemplified by revised Experiment 3

Screen design for first screen of Experiment 3



Following his first two experiments, Hammerling wanted to establish whether it is the nucleus or the rhizoid which controls *Acetabularia*.

Use the notebook tool to suggest an explanation for control of development in *Acetabularia*. Your model should be supported by background science explanations (some suggested explanations are available from the science explanations button).

2 cm

Acetabularia mediterranea

INSTRUCTIONS SCIENCE EXPLANATIONS RESET NOTEBOOK

Screen design for workbench tool, Experiment 3



Introductory screen for Experiment 3 and workbench tool to encourage students to investigate whether it is the nucleus or the rhizoid which controls development

PCDK

The notebook button links to notebook tool where a two column tabulation provides activity spaces for the 'before' and 'after' models of control of development. The instructions for articulating an explanatory scientific model on the first screen are repeated in the notebook tool. The notebook tool has links to background science models from a button 'Science explanations'.

The 'Next' button from first screen of Experiment 3 takes you to the second screen, which is a manipulable workbench animation of the experiment. It provides instructions in a pop-up box from a button, and pop-up guidance on the tools and techniques relevant to this experiment. For example, the scalpel tool allows the cell to be cut into three parts, the pipette allows you to remove and replace the nucleus in any section of the cell. The Petri dish allows you to 'develop' a cell or cell part.

The 'Next' button from the workbench takes you back to the notebook – where instructions in the tabulated section for Experiment 3 direct students to reflect on and revise their model in light of their experimental results.

Notebook screen design

Text for notebook screen: Use the notebook tool to revise your initial model. Suggest how the evidence from your experiment supports or refutes your initial model. Suggest a revised model backed up by background science ideas and evidence from your experiment (use the science explanations button).

Initial explanation for control of development in <i>Acetabularia</i>		Revised explanation for control of development	
Explanation	Supporting science	Explanation	Supporting science
PDK	CDK	PCK	
<p>From Quintana <i>et al.</i> (2004):</p> <p>Using representations and language that bridge with prior learning</p> <p>Using representations that learners can inspect to reveal important properties of underlying data</p> <p>Providing structure for complex tasks and functionality</p> <p>Embedding expert guidance about practices of the domain</p> <p>Facilitating ongoing articulation and reflection during learning.</p>	<p>Animations which communicate the processes of the Hammerling experiments.</p> <p>Formalised visuals which communicate specific structures using scientific conventions.</p> <p>Hyperlinks which allow non-linear navigation to a range of information and tools.</p>	<p>PCK implicit in the experiment simulation:</p> <p><i>Acetabularia</i> is large enough that it can be manipulated to investigate which part of the cell controls development.</p> <p><i>Acetabularia</i> can be dissected, cells parts rejoined and the nucleus transplanted to different parts of the cell. Whole cells or parts of the cell can be grown in a Petri dish.</p> <p>Scientific inquiry processes lead to the deduction that chemicals produced by the nucleus move into the cytoplasm and control development of the hat in <i>Acetabularia</i>.</p> <p>PCK of explanatory models is accessed from the Science Explanations button:</p> <p>The controlling chemicals in the cytoplasm are proteins produced by transcription and translation of the genetic code in the nucleus.</p> <p>Enzymes which catalyse chemical reactions in cells and structural proteins are both involved in development.</p>	
<p>References</p> <p>Sweller and Chandler, 1994; Ogborn <i>et al.</i>, 1996; Schwartz and Bransford, 1998; Sutton, 1992; Windschitl, Thompson and Braaten, 2008.</p>			

6.9.1 Displaying complex information and relationships

The tabulated model for PCDK above includes information at a level that could inform initial design consultations, and might be used to describe final designs for reference by other designers. It provides the content, design and rationale for the design, including references to literature.

The amount of information involved in displaying educational activities with their design annotations is an issue which has a potential solution in web-based software. The tabulated version of PCDK may be appropriate for paper-based publications, but the need for information which is presented in a way that allows users to drill down to access greater detail or for different purposes suggests the affordances associated with hyperlinks and electronic solutions.

Described below is a suggestion for the type of interactive interface which would allow designers to link their designs, case studies and references to underpinning literature and commentaries to the generalised guidelines for specific areas of science educational design.

Interactive visual interfaces

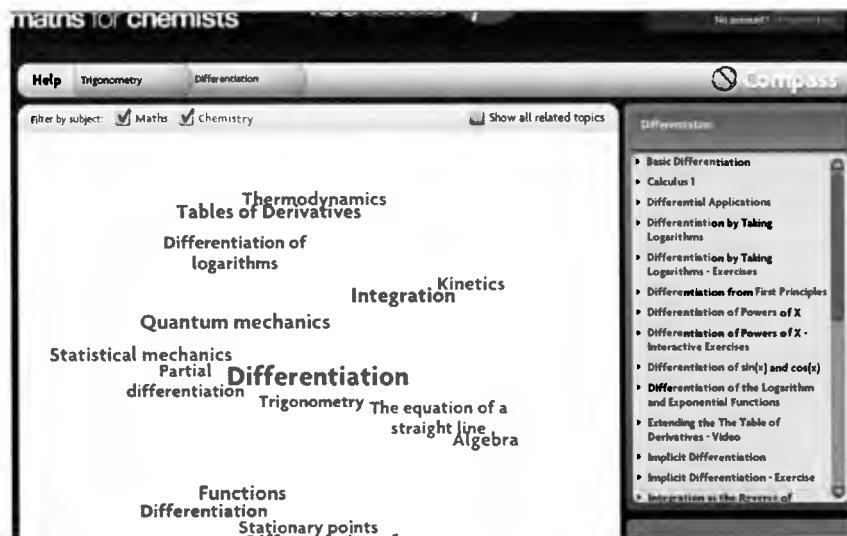
The Royal Society of Chemistry's (2009) *Discover Maths* project has a visual 'compass' tool which displays the connections between chemistry (in blue/ darker) and maths (in red/ lighter) (Figure 6.12). This tool is relevant because it shows how two domains can overlap but still allow easy drilling down through the topics to examples. A similar approach could be used to show the relationship between designs, specific content, application of pedagogic approaches, technological tools and underpinning research.

Spicynodes¹⁰ (IDEA, 2011) is another Flash-based visual navigation system which would allow a similar solution with complex connections between elements. Similarly, Stefaner Moritz's

¹⁰ SpicyNodes technology is based on research into human learning showing that having control over a learning situation, such as choosing the nodes in the interactive SpicyNodes maps, turns on parts of the brain which become involved in actively exploring the world. Having control in this way enhances the way humans perceive and learn about phenomena (Voss et al. 2011).

(2011) approach to 'information aesthetics' provides a rich source of solutions using interactive visualisations.

Figure 6.12 RSC's Compass tool in 'Discover Maths'



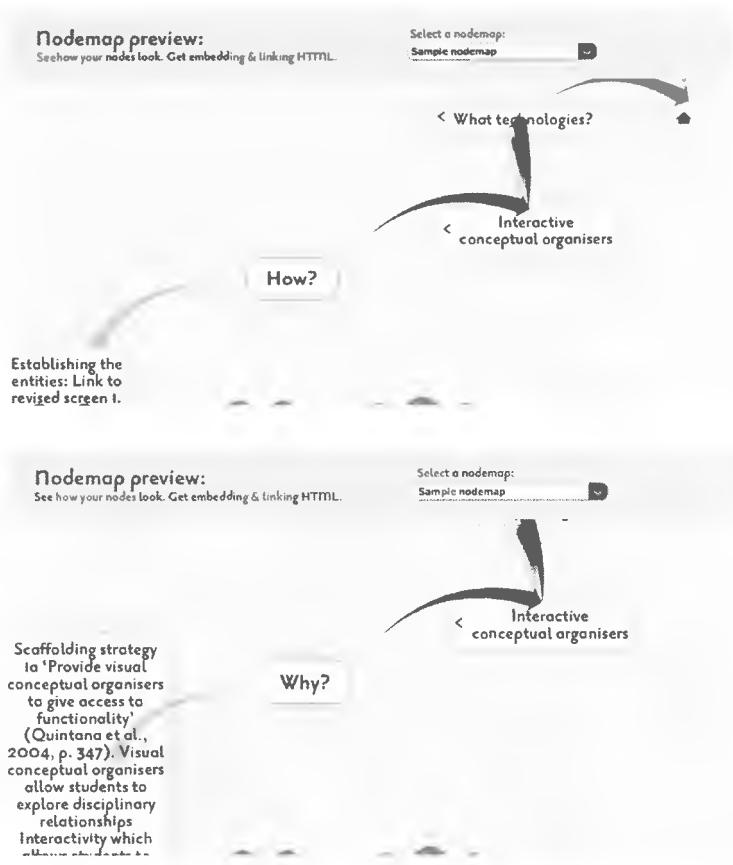
Complex information can be presented through the navigable maps in SpicyNodes. Draggable windows allow the user to navigate to different nodes, making these central in the window, and bring up further subnodes. The screenshots in Figure 6.13 show how a central node 'Designing software for science inquiry' can lead to further nodes, which can themselves be expanded. With the aim of displaying the new combined didactical framework based on Hudson (2008) and Quintana *et al.* (2004), the nodes could end in links to exemplar screens with their annotations about design heuristics, relevant literature and task models. The software could allow users to add their own exemplars at a node, and to annotate these examples for the benefit of other designers.

The navigation afforded by this type of interface allows users to enter and follow the threads of information and exemplifications according to their need and interest. Frequently, design is based primarily on subject content (for example, a need to 'cover' a particular topic of a course) so designers could enter through the topic content nodes ('What content?').

Alternatively, teachers may wish to read more about the underpinning pedagogies, and designers may want to see applications of particular technological tools.

Figure 6.13 Spicynodes screens which show drilling into a topic (design of software)





A specific design may be approached through any one of the nodes, depending on the focus taken by the user. So, for example, the screens which exemplify establishing *Acetabularia* as an entity would be added and annotated for access from the node showing scaffolding strategy 1a. Other screens, or even the whole resource, might be accessible from different nodes. Later designers with a different focus might add their own links to the tutorial as they suggest how it exemplifies other features, for example the affordances of animation or small group work.

6.10 Summary of inferences from this study

The data from this study suggests that ICT tutorials can offer tools to develop inquiry processes separate from the noise of wet practical work. In particular these tutorials provide an opportunity to show how science develops, by using classic experiment to illustrate the development of ideas. This study has shown that the *Acetabularia* tutorial can be used to exemplify scaffolding strategies in the Quintana et al. (2004) framework.

This study showed that student data can provide evidence of learning and barriers to learning to inform design. This data was used to critique the design guidelines in the Quintana *et al.* (*ibid*) framework, and to suggest how it could be developed further. For example, the scaffolding design guidance needs to make explicit how the background science ideas which make sense of an inquiry are to be accessed by students when the tools only support the processes of inquiry. The study demonstrates the utility of generic, principled frameworks for design, but emphasises how scaffolding design cannot be viewed independently from other pedagogic, domain content and design considerations. These considerations and the relationship between them need to be articulated as part of the design process. The holistic pedagogical model developed in this study (see Section 6.7) shows how these relationships could be considered during design. This chapter also suggested that interactive technological tools might be useful for displaying exemplar resources and their annotations in a way that is useful to the design community.

The didactical design model suggests the notion of pedagogic content design knowledge (PCDK), which is the complex, applied knowledge that designers bring to educational design. The model for describing the elements of PCDK in this chapter provides a heuristic for design, and a framework for analysis or evaluation. The resulting model is more holistic and explicit than either of the contributory models. The Quintana *et al.* (*ibid*) scaffolding design framework unpacks the pedagogies underpinning scaffolding tools which the Hudson model (2008) considers in association with specific content and broader pedagogic approaches.

During this study it has emerged that the vocabulary needed to describe both the task models for what needs to be learnt and the pedagogies for science inquiry learning are not well defined. For example, the science education community could benefit from a clear articulation of the task model for developing scientific explanations.

A model-based paradigm for science inquiry is used to underpin the approach to developing causal explanations in the suggested revisions to the tutorial in this chapter. This approach is based on a more authentic interpretation of the scientific method than is sometimes used in science lessons, and provides a pedagogic solution to using scientific models in science inquiry learning.

An agreed set of task models for background science content would also benefit teachers and designers. These need to involve both detail of the nested topics and subtopics, and the

overarching big stories of science. The AAAS (2001) concept maps provide an example of work in this area, but more needs to be done to define how scientific knowledge can be transformed into the content of science education. For this we can look to the European Didactic tradition, which considers how content should be transformed for learners.

This thesis started with a discussion of how educational design needs to establish itself as a discipline alongside mainstream educational research. By proposing an area of knowledge to be acknowledged as PCDK, by showing how an existing framework sits within a new, more comprehensive didactical model, and by showing how an interactive database can be used to gather and communicate the complex knowledge base involved in PCDK, the thesis contributes to the development of educational design and capacity building in this field.

Chapter 7 Reflections and ideas for further work

7.1 Contributions of the thesis

This study contributes a methodology for a principled approach to designing, evaluating and improving educational designs. It provides a case of how generic design principles can frame analysis of empirical data, and the affordances of this type of analysis in the design process. Specifically, the study demonstrates how the methodological approach of using an in-depth analysis of an electronic tutorial against an existing framework exposes the affordances and shortcomings of the framework and the tutorial. As a result, revisions to the Quintana *et al.* (2004) framework and to the *Acetabularia* tutorial are suggested.

The study showed that the *Acetabularia* tutorial from the SNAB course resources could be added to the exemplifications in the Quintana *et al.* (2004) scaffolding design framework to extend its scope. It validated the framework's task model for science inquiry learning, by demonstrating common inquiry tasks characterised in the framework and the *Acetabularia* tutorial task model.

Inferences from the study include the need for a more structured approach to developing and sharing the craft and design knowledge of educational designers. The proposed methodology includes a decomposition of the applied craft knowledge of educational design (PCDK). The detailed analysis approach taken is justified by the need for much more specific guidelines to assist designers and to support the building of PCDK. The study also highlights the need for science inquiry learning to be framed by explanatory models, and shows how this might work in practice through suggested revisions to the tutorial.

7.2 Evaluating a methodology for principled educational design

This chapter reflects on the methodology and findings from this study, along with ideas for further work. This study led from a consideration of how to evaluate software developed for

the SNAB course. While students and teachers expressed enthusiasm for the software component of the resources, the pilot evaluation and other contact with SNAB teachers did not lead to any critical or reflective comments which might directly inform revisions or further development.

Chapter 1 highlighted the need for educational design to be underpinned by principles from educational research. The research question articulated at the end of Chapter 1 was 'To what extent can generic principles frame educational design?'. The approach used in this study tested an existing scaffolding design framework on the basis that educational designers should work towards agreeing principles and heuristics for design. The study also reflects a general issue in educational design, which is the need for the craft and knowledge of the discipline to be articulated and shared. The research question is answered in Chapter 6, which shows how greater detail can be provided to designers through annotated cases which exemplify generic guidelines.

The chosen approaches in this study contrasted with earlier pilot studies which explored a more positivist, experimental methodology. Pre and post testing was used to compare learning through two software tutorials and an equivalent paper-based activity. This approach revealed little significant difference between groups, and little information that could be useful to designers. Knowing that students who have followed a particular approach perform better in specific test questions than those using a different one does not reveal which specific design features are more effective or why they are effective. This reflects the discussion in Chapter 2 comparing the efficacy of large scale versus small in-depth studies for educational design (Section 2.2). It also reflects the need discussed in this study, for science inquiry learning to be framed by explanatory models: in the same way, design research needs to be framed by theories which throw light on the affordances of design features, and comparative studies looking at student performance may well contribute to these.

7.2.1 The review of the literature

A review of the literature highlighted studies of learning through science inquiry and pedagogic approaches which could be applied in educational design. The review focused on literature pertinent to the affordances of software in scaffolding science inquiry learning, as the *Acetabularia* tutorial chosen for this study was based on a classic inquiry. The Quintana *et al.*

(2004) scaffolding design framework provided a distillation of previous work on scaffolding learning through science inquiry, and, as such, was chosen to frame the study.

As the study developed, broader questions emerged about the underpinning epistemology of science inquiry learning and the specific barriers to learning evidenced in the context of the *Acetabularia* tutorial. Drawing on literature beyond the scope of the framework's references was necessary to explain the observations in the data and to suggest design solutions.

For example, literature on misconceptions associated with the specific background science content threw light on the barriers to learning where students showed confusion about what *Acetabularia* is. The literature on cognitive load theory provided an additional and useful explanatory underpinning for scaffolding strategies in the framework such as restricting the task (Guideline 4) and making the processes of the discipline explicit (Guideline 5).

Where the guidelines suggested that visuals and language should build on learners' intuitive ideas (Guideline 1), the literature on visual literacy and use of technical language underpinned important ideas to consider in designs which develop students' understanding of background science ideas.

This study restricted its attention to how students form explanations using background science. It has shown that the literature base which informs the translation of this learning aim into software tools extends beyond science education, involving generic pedagogic approaches, affordances of different technologies and the role of teachers in an ICT-based classroom. Within the scope of this thesis, the literature review informed the inferences from the data, including the practical outcomes from the study. How the analysis contributed to suggested revisions to the framework and the tutorial is evaluated below.

7.3 Testing the scope of the framework

This study tested the Quintana *et al.* (2004) scaffolding design framework against empirical data from students using a software tutorial based on a classic inquiry. Quintana *et al.* (*ibid*) invite testing of their framework, seeing it as a proposal for how design guidance could be articulated and presented.

Scaffolding guidelines in the framework successfully informed analysis of the scaffolding in the tutorial. In particular, the guidelines helped to illuminate the multiple choice questions in terms of structuring and restricting the task (see Section 5.4.2) and raised the issue of linking with students' prior learning when developing explanations.

It can be concluded that the broad principles in the framework were relevant to the *Acetabularia* tutorial. The *Acetabularia* tutorial could be added to the exemplifications, to extend the scope of the framework. The study suggests that the principles should be applied to background science in addition to science inquiry processes. It suggests that exemplification of scaffolding of background science should be included in the framework.

The study also concludes that the scope of the framework is limited by lack of detail in its guidance, and by its consideration of a single element of software design in isolation from the wider process. Chapter 6 showed how a scaffolding design framework could sit within a more holistic model which integrates pedagogical approaches, consideration of the content of learning and the affordances of technologies.

The utility of the suggested format for extending the framework (see Section 6.9), through collection and communication of design knowledge, its exemplars and annotations, still remains to be tested. The aim would be that the structure of a web based framework would be agreed by the educational design community. It could frame iterative, principled development, and would encourage dialogue within the community. Designers could add their case studies, examples and annotations, and suggestions for further work. Literature which designers have drawn upon could be referenced along with their work. This concept needs discussion and refinement within the relevant design community, and, ideally should encourage participation from the educational research community.

The methodological approach in this study uses analysis of student performance data to critique both the principles in the framework and the tutorial's design. It was this in-depth analysis which led to the generation of a more holistic framework that would provide better support to designers.

The proposed integrated design model is one of the contributions of this thesis. By defining and exemplifying pedagogic design content knowledge (PCDK), and by showing where these

elements integrate in the design process, this study has shown that the constituent knowledge of educational design can be made explicit. The study demonstrates the utility and scope of generic principles, through defining their role in PCDK and showing how they can be applied to revisions of a tutorial, exemplifying a specific case.

The construction of a didactical design model based on Quintana *et al.* (*ibid*) and Hudson (2008) addresses limitations of both models. It sets the Quintana *et al.* (2004) framework within a broader design context, and shows how aspects of the Hudson (2008) model can be unpacked further. Quintana *et al.*'s (2004) framework unpacks scaffolding design within the pedagogical considerations of the Hudson (2008) model. In a similar way, the paradigm of model based inquiry guides the approaches of the revisions, as a further pedagogical consideration. A way of communicating this knowledge is suggested, using a web-based visual interface.

7.4 The utility of the framework

The utility of the original framework as a guide for analysis of scaffolding in a tutorial and analysis of empirical data was demonstrated in this study. The process used to construct the framework was mirrored in the analysis in this study. The original task model for the *Acetabularia* tutorial was developed with reference to the AAAS inquiry processes as defined in their Project 2061 curriculum mapping (AAAS, 2005) (see Section 3.2). This process validated the framework's task model, by demonstrating common inquiry tasks characterised in the framework and the *Acetabularia* tutorial task model.

Comparing the student data against the task model for the tutorial helped to identify learning and barriers to learning. The learning and barriers to learning were compared with the scaffolding design guidelines in the framework. This demonstrated the utility of the framework in guiding analysis of the scaffolding present in the software, which in turn informed the analysis of the data.

For example, the data showed that students struggled with some scientific terms used in the tutorial, and were confused by the visual of *Acetabularia* (see Section 4.2.2). The problem of insufficient support linked to scaffolding strategy 1b 'Use descriptions of complex concepts that build on learners' intuitive ideas' (Quintana *et al.*, 2004, p. 345) was used to explain students' confusion. Guideline 4 'Provide structure for complex tasks and functionality' (p. 345)

highlighted the challenge of drawing on relevant prior learning to explain observations in the experiments.

However, this methodology raised the issue of how the inquiry task is being defined, and at what level of granularity. The task model on which the framework is based does not define the task of explanation, for example, in enough detail to guide scaffolding. The generic processes which categorise the guidelines are only useful if the designer has a sufficiently detailed breakdown of sub-tasks for each inquiry process to be scaffolded. This study suggests that more detailed guidelines, and more exemplification through case studies would be useful, to demonstrate the processes that designers need to apply as they use the scaffolding design framework.

In conclusion, the study contributes a case of how generic design principles can frame analysis involving empirical data, and how this analysis sits in the design process.

7.5 Limitations of the research

The main limitation of this study is its scope, restricted to the example of a single electronic tutorial and, within this, to a single element of science inquiry learning. By raising some issues around the pedagogies, content and design of science education software resources it points to the need for further development of this work and related studies.

The tutorial chosen for this study represents learning through a classic inquiry that students could not carry out in a school laboratory. The choice of the *Acetabularia* tutorial could be questioned, as the Quintana *et al.* (2004) scaffolding design framework sets out to scaffold inquiry learning. Whether or not the tutorial represents inquiry learning is debatable. The justification for using the tutorial is in the suggestion that it represents extreme scaffolding suitable for early stages in learning inquiry processes, or for engaging with an inquiry in an unfamiliar context. The fit of the data with the framework's guidelines highlights how the tutorial provides partially completed activity spaces for some inquiry processes, allowing students to engage in highly restricted inquiry tasks.

Critique of the methodology

As discussed in Section 7.3 assumptions made in the methodology used in this study include the idea that there is a match between what the Quintana *et al.* framework (2004) aims to guide and the aims of the tutorial. The gaps identified in the framework could lead from the differences between scaffolding for an open inquiry and a highly structured electronic tutorial. To validate the findings from this study, the methodology needs to be tested in a wider range of contexts.

Inferences from this study rely on the quality of the data. In making the inferences, there is an assumption that collection of recorded data is relatively neutral. Even so, data collection involves the decision about how many students to record, and the method used to select these students. The selection of students to record in this study was random, using numbers from the class register, although the individuals selected could choose their partner to work with. The number of recordings was limited to allow for detailed analysis within the scope of this study.

The chosen approaches to this research imply a position which values the rich analysis of a small sample of data for the particular purpose of this study. This is not to exclude the potential for large scale studies to validate design approaches of particular interventions in some situations.

Students' discussion of the entire activity was recorded as they worked in their pairs. The recordings of the discussions during the tutorial and post interviews were transcribed verbatim, so, again, no selection was made in this process. Even so, there are assumptions made when using audio recordings as data. For example, it is assumed that the data is typical of students in the wider group carrying out the *Acetabularia* tutorial, both in the particular situation of the study and to some extent of students more widely.

In this study, there are examples of the phenomena of interest across the transcript data from different students. The consistency of the appearance of certain phenomena allows a claim for generalisability to be made, while understanding that sample size is always a compromise between validity and the resources available for any study. Collection of different forms of data also proved successful as a way of validating initial interpretations. The transcript data was compared with similar phenomena identified across a larger sample of written data.

The transcription stage of the methodology does not assume that transcription is a neutral act. Any utterance can be heard in many different ways (Freebody, 2003), and tape recordings are only a selection of the information present at an event. Minimal punctuation is used in the transcriptions in this study, but any punctuation imposes an interpretation of meaning. For example, question marks are used where the context and intonation imply a question is being asked. Visual clues and the context of the social situation, for example, are missing from audio recordings. On the other hand, the video recordings of screen actions, along with their transcripts, do allow actual, naturally occurring interactions in educational settings to be studied in detail, along with aspects of their context.

A further consideration to be taken into account as the data in this study is interpreted is that, although the classroom context was as natural as possible for this study, the students knew they were being recorded, and the microphone was in front of them, reminding them of this.

In summary, the inferences from this study could benefit from repetition with a larger data sample, and the methodology could be refined through testing it in a wider set of contexts. The methodology could also be tested starting from different points in the design process. This study started with an existing design with the purpose of informing revisions. A similar methodology could be used for initial designs and for analysis of student data for purposes other than design (for example for evaluation of educational resources).

7.6 Ideas for further work

7.6.1 The role of teachers

Back in 2004, when the SNAB electronic resources were first being developed, the issues around use of software raised in the evaluation of the course (Lewis, 2004) included access to computers and technical support, and confidence in using ICT (Section 1.5). Around this time, Norris *et al.* (2003) suggested that teachers' use of technology in the classroom is 'almost exclusively a function of their access to that technology' (p. 25).

The uncertainty around the role of teachers in classrooms that use ICT was also evident as an issue in the evaluation of SNAB, and is an important issue for educational design. Developers need to decide whether software for learning is intended to stand alone, providing the guidance

necessary for effective learning, or, whether guidance on how to facilitate learning effectively using the software should be provided for teachers alongside the software. This need is exemplified by a comment from the SNAB pilot study:

“[it’s] almost distant learning. I’m struggling to find where my input fits in – which bit am I teaching? Part of this comes down to my definition of what teaching is” (Teacher 8)

(Lewis, 2006, p. 104)

The original design of the SNAB software recognised its potential use in small group work. It saw tutorials which move learning on for most students, most of the time as providing an opportunity for teachers to work more intensively with small groups or individuals. Computer based activity could allow tasks which need more teacher guidance to take place in parallel. For example, one lesson observed during the data collection period included a lesson where students carried out a tutorial on measuring blood pressure, while two pairs of students at a time accessed the two blood pressure monitors that were available. The use of the electronic component of the SNAB course has seen a range of uses, which include small groups or pairs at the computer, being led by a teacher from a whiteboard at the front of the class and individual student study at home.

This lack of clarity about the teachers' role, frequently led to teaching that covered the same content as the software tutorials, and resulting complaints that there were too many activities to fit in (Lewis, 2002). This can be interpreted as teachers' lack of involvement in the computer-based learning activity resulting in lack of appreciation of what has been learnt. This effect is not necessarily restricted to software, but applies to any student-centered learning activity.

The idea of being a 'guide on the side' (Doolittle 2003) has been with us for many years, but this study has concluded that software scaffolding needs to support the introduction of new concepts as the 'sage on the stage' in addition to guiding process management. The answer to what the teachers' role should be when students are engaged at a computer is similar to this consideration in relation to non-ICT activity. The difference is that software scaffolding has the potential to take on additional aspects of a teacher's role, including prompting, guiding and providing feedback and hints. Software can actively structure the learning, and present new

information through media such as animations which may have enhanced cognitive affordances compared with teacher talk and text books. ICT also has motivational advantages (Becta, 2003). But, the computer becomes an active participant in the learning dialogue, and the teacher may feel left out of this. Designers can't make assumptions about teacher presence, as the final software tools must cater for a range of learning environments, so the solution lies in communicating to teachers how software can be integrated into their lesson sequences.

Active, student-centred learning needs a conscious approach by the teacher to set up and mentor the experience and resulting learning. Teaching practices are not changed automatically when ICT is introduced. New teaching and learning approaches need to be adapted, through reflective practice and feedback (Moseley *et al.*, 1999). The role of the teacher when SNAB ICT tutorials are deployed will depend on the teacher's understanding of the role of the tutorial. Teachers may, for example, believe that good quality experiences through presentation of new knowledge with multi-media will automatically lead to assimilation of that knowledge. Students fully occupied at computers, motivated by a change in mode of delivery, give the impression of studious learners. A teacher who acknowledges the role of peer or teacher-student interaction during learning will be a more active participant during their students' activity at the computer. The classroom will be set up to allow paired or small group discussion, or, if the activity is carried out as a whole class, breaking into smaller group work at suitable stages allow active application through argumentation and problem-solving.

The concept of situated learning (Lave, 1988), where the learning is a product of the way new knowledge is presented and of social interaction and collaboration, suggests that evaluation of learning resources in a normal classroom environment must specify the conditions of deployment and position of the activity in a teaching sequence. It should refer to student's prior learning, and be specific to the mode of deployment of the activity.

An ICT tutorial can be related to the modes of teaching and learning approaches defined by Gagné (1970), who categorised the patterns of interactions of learning modes, the main ones being

- tutorial: two-way interchange between tutor (Teacher) and tutee (Learner)
- lecture: one-way information flow from source (Teacher) to many receivers (Learners)

- discussion: two-way interchange among Learners
- laboratory: Learner acts on raw materials (Resources)
- independent study: Learner acts on encoded, instructional materials (Resources)
- practice: Learner uses new skill repeatedly (may be guided by Teacher).

These modes and patterns of interaction tend to be associated with different stages in a teaching and learning sequence. A practical experiment or simulation might be the stimulus at the start of a new topic, where a project or practice activities are more student-centred applications of learning. Teacher lectures tend to be used to present new information; discussion can help learners to apply new learning. The role of the teacher will depend on the approach chosen, and the role of an ICT tutorial will depend on the teachers' ability to integrate these into their normal practice.

Laurillard (2004) lists an optimal learning process, to include a discursive process between student and teacher, discussed in Section 2.2. In the absence of a teacher, this 'conversational framework' described by Laurillard can take place as a thought experiment through an individual student's internal dialogue. ICT may be able to provide elements of scaffolding for the conversational framework, and using this framework for analysis of the process could help assess the affordances of the new media compared with traditional approaches.

Teachers' views of how to deploy ICT tutorials might see tutorials as expositions of new ideas, equivalent to teacher lecture. The tools within the software might involve visuals or multi-media enhancement where the information flow is unidirectional. Other categorisations of the role of software depend on the design and mode of deployment of the tutorials: if students work in pairs, there may be considerable two-way exchange between students. Alternatively, learning will be independent if the tutorials are carried out for homework.

Good ICT-based feedback can potentially produce interaction between students and computer approaching two-way teacher and student exchanges. The quality of electronic feedback is unlikely to be as rich as interaction between teacher and student, but the immediacy and quantity of feedback available through ICT programmes may exceed what is possible in most classrooms.

Much of the guidance for designers that forms the annotations and references in the revised interactive didactical design framework (Figure 6.3) is also relevant for teachers. The discussion around pedagogies, approaches to science inquiry and scaffolding learning could help to inform teachers' use of the resources, and other similar resources. For example, where the role of a resource is described, a teacher could choose to replace this with an alternative approach. So, if the framework describes a set of screens as promoting articulation and reflection on a particular point, the teacher can replace this with class discussion.

The literature supports the view that that the key to effective teaching and learning online is that the integration of online learning should transform existing practice rather than merely translate existing practices (Petre et al., 2004; Fetherston, 2001). With reference to the didactical model for PCDK presented in the last chapter, the teacher presence should be considered as part of design. Pedagogy needs to be considered in relation to each aspect of an activity, but also with reference to building the big narratives of science through a lesson sequence of which an ICT tutorial is one small part.

Any successful transformation in educational practice relies on a change in teachers' attitude. The development of positive attitudes is necessary if teachers are to integrate use of software into their repertoire, and to avoid resistance to its use (Woodrow, 1992; Watson, 1998). Demetriadis et al. (2003) concluded that consistent support and extensive training is necessary to provide teachers with the confidence to integrate ICT into their teaching. Future studies on the affordances of ICT resources could usefully consider the broader community effects such as the changing roles and rules associated with the classroom when computers are introduced. In addition, designers' annotations could encourage teachers to challenge assumptions made about the use of software in classrooms, such as whether it has to be stand-alone, used for group work or used from the front of the class.

The next section discusses the role of software and its relation to teacher presence in the context of articulation and reflection, as the implication that software needs to be designed to replace some of the functions of a teacher in promoting this activity is salient to the discussion of the role of the teacher in a classroom using ICT.

7.6.2 Scaffolding articulation and reflection

Software design is able to provide the flexible levels of scaffolding and feedback to structure collaborative learning. The questions and tasks in the SNAB tutorials can act as 'collaboration scripts' to encourage these learning activities. Between the ICT tutorial and the accompanying student worksheet, the interaction between students is structured. This 'scripted cooperation' framework has been adopted by many researchers and educators in the field of computer-supported collaborative learning. Dillenbourg (2002) defined five levels of coercion or control of the user in supported collaborative learning through scripts present in computer-based resources. These range from 'induced scripts', where the interface only implicitly conveys the designer's expectations for how to tackle the problem and interact with each other, to 'follow-me' scripts at the opposite extreme. In 'follow-me' scripts the environment does not allow students to escape from the script.

This high level of coercion is present in the existing SNAB tutorials. Students have to agree on only one possible answer to the multiple choice questions, the tutorial does not allow students to answer in another way, and they can only move on to the next stage once they have completed the previous stage. The revisions to the *Acetabularia* tutorial suggested in Chapter 6, such as the more open, work-bench versions of Experiment 3, open up the student guidance towards induced scripts. These scripts at the lower end of coercion will not automatically encourage discussion, articulation and reflection, so software scaffolding in tutorials should support the process of knowledge construction as students are engaged in solving meaningful problems.

A consideration of the teacher's role in this type of constructivist learning should guide the design of software for learning: ICT tutorials should aim to engage and mentor students as they construct their own meaning. This shifts the responsibility for learning away from the learning resource (or teacher) as a behaviourist transmitter of information, towards the student as an active constructor of knowledge (Reynolds and Sinatra, 2005).

Software can be a tool for individual 'homework' study, but teachers should be encouraged to explore its use as a tool for stimulating group discussion. Complex mental processes take place during social activity, so learning with social interaction goes beyond learning that can take place with an individual working alone. Anderson's (2001) situated cognition theory describes

group schemata, based on research studies of group discussion. Arguments suggested by one member of a group were taken up very quickly by others. This resulted in a 'snowball effect', where the group shared a schema introduced by one individual. The speed of this type of schema creation during group work contrasted to individual work, where repeated experiences were necessary to achieve the same learning outcomes.

Independent learning is associated with software, and is often confused with learning alone, but the ability to make the most of a collaborative learning situation is an important element of autonomous learning which students develop through practice. This applies to using ICT tutorials just as it does to other types of learning activity.

Successful collaborative learning relies on effective interaction of learners. Unless directed by a teacher or activity script, learners are unlikely to ask each other questions, reflect on their knowledge or explain and justify their opinions. This articulation and reflection is a main categorisation of scaffolding in the Quintana *et al.* (2004) framework.

This process of active and collaborative learning lends itself to being supported by immediately available prompts, hints and feedback possible using software. Articulation and reflection can be encouraged through activity spaces which students type into, as in the WISE (Web-based Inquiry Science Environment) software (Linn and Slotta, 2000). This approach was used in the revisions to the SNAB tutorial shown in Chapter 6, where a notebook tool structures articulation and reflection as students develop explanations.

This study suggests that there is a role for unpacking the individual elements of PK, and in particular articulation and reflection. For example, Chapter 2 uses the literature to suggest that feedback in software tutorials can't match the adaptive feedback which teachers can provide, but should aim to complement the teacher (Sandoval, 2003). There is scope for guidelines which help designers to explore what 'complementing the teacher' means, and how this can be applied in the design of software tutorials.

Software needs to be designed to be adaptable to different modes of deployment, and different levels of external scaffolding. Designers could provide explicit guidance on how they see their design being used optimally. Such guidance alongside educational software could help teachers to appreciate the designers' interpretation of where feedback and articulation and reflection

are needed, and where they have assumed the teacher will prepare for and follow-up the tutorial within a teaching sequence. An idea of where the tasks are particularly challenging or complex would help teachers to make a judgement about how they might intervene to complement the tutorial.

This study has shown how the separation of articulation and reflection, sense making and process management in the Quintana *et al.* (2004) framework allows useful consideration of the scaffolding approaches which relates to each of these, even if these elements of pedagogic knowledge (PK) overlap once applied in the design of activities for learning. This decomposition of the elements of PCDK is at the heart of the didactical model for design suggested in Chapter 6.

Further work could explore the different elements of PK as they cut across each other and across content knowledge (CK) and design knowledge (DK). The interactive visual navigation tools suggested for displaying and annotating designs according to the PCDK model, suggested in Chapter 6, would allow exploration of designs according to a range of cross-cutting themes based on tools, pedagogic approaches or content topics.

7.6.3 Exemplifying barriers and lack of scaffolding

This study used evidence for barriers to learning to suggest revisions to the tutorial. It follows that it would be useful to designers if the framework exemplified barriers to learning and insufficient scaffolding in addition to examples of software scaffolding tools. This could help to alert designers to examples of insufficient scaffolding in addition to appreciating where scaffolding is successful.

The task of analyzing alpha versions of designs and using evaluation studies to identify gaps in scaffolding of existing software suggests an important potential role for the framework. But, even in initial design, seeing examples of what to avoid is as informative as examples to follow. Examples of insufficient scaffolding may also support less experienced designers to discuss what is needed to improve their scaffolding designs, restricting the task of designing scaffolding from scratch.

7.6.4 Articulating tasks and subtasks at a sufficient level of detail

While concluding that generic principles have a role in educational design, the study highlighted the need for a higher granularity of task model to characterise tasks for the purpose of designing scaffolding. Although the detailed discussion of the elements of science inquiry are beyond the scope of this thesis, designers need science educators to agree upon and articulate the task models for individual tasks and subtasks within inquiry learning if they are to support this with effective resources. The example of causal explanations was raised specifically in this study. It would be useful to articulate what types of explanation students should be expected to construct at each level of their education and at particular stages in an inquiry. Designers can then develop heuristics for supporting students as they learn to construct explanations, and these heuristics would provide a basis for learning activities. The multiple choice questions in the *Acetabularia* tutorial demonstrate one example of how the heuristic for linking evidence and conclusions can be applied in task design (Section 4.2.3).

7.6.5 Scaffolding background science ideas

The discussion in chapters 5 and 6 pointed to the potential for the existing scaffolding design guidelines in the framework to support different areas of content. A suggested extension to the framework emerging from this study, is to acknowledge the need to scaffold background science ideas, and to add exemplifications of software which demonstrate the affordance of the guidelines for this area of content.

The more fundamental revision suggested is to define a paradigm for learning through science inquiry which acknowledges a more authentic version of the scientific method. The barrier to developing a pedagogy which integrates authoritative expositions of background science into inquiry is possibly as a result of the flawed, inductivist model which underpins some current practice. The paradigm suggested for the revised guidance is model based inquiry, which sees science inquiry as testing and refining scientific models (Windschitl, Thompson and Braaten, 2008). The science education community can contribute to translating model-based inquiry into classroom activity, and to defining and agreeing the scientific models which we present to students. As suggested by the discussions on the proposed model for PCDK, the European Didaktik approach should be referred to, along with the associated body of literature on transforming content for learning.

7.6.6 PCDK

Building on this discussion, the pedagogy of science inquiry goes beyond scaffolding, and the knowledge needed by designers goes beyond pedagogy. Designers need to adapt their knowledge of pedagogy to specific content, and apply their design knowledge to both of these. Chapter 6 proposed the area of PCDK (pedagogic content design knowledge) to describe this domain (Section 6.5.2, p.186).

As part of PCDK, Chapter 6 also suggests that the science education community lacks a consistent approach to pedagogies which support specific areas of content. Recent work has emphasised generic approaches such as discussion, argumentation and practical skills, all of which should contribute to the targeted pedagogies. More work is also needed to articulate the pedagogies which decompose the big ideas in science to make their nested entities explicit. Studies of students' misconceptions are useful here, as are existing curriculum maps, but there is a need to go beyond research to implementation of designs which use this knowledge to provide effective support for learning.

7.6.7 Establishing and maintaining a community for educational design

This thesis has achieved a deconstruction of the process of educational design, which reveals the complexity and richness of this field. The importance of good quality educational design relates to the unacceptably large variation in learning opportunities that can still be found across classrooms. To some extent, the issues of consistency across the educational system can be addressed through shared aims and through shared 'knowledge products' (Morris and Hiebert, 2011). The knowledge products described in this thesis are instructional products, their underpinning design frameworks and the outcomes of testing these though empirical research.

The continued development of educational design communities such as the International Society for Development and Design in Education (ISDDE, 2011b), and journals such as the electronic *Educational Designer* (ISDDE, 2011a) should be encouraged, as should greater collaboration between education researchers and educational designers. One way of achieving this would be to encourage articles based on specific educational design studies to be adapted for both journals with a research focus and journals with a design focus. Design themes could be encouraged in science education conferences. The aim would be for a more informed and

collaboratively developed knowledge base for international educational design and development.

By establishing the affordance of general design principles and proposing a didactical model to frame these principles, and by exemplifying how the conditions applying to their use can be explored and refined, this study has sought to make a contribution to the knowledge products of educational design, which in turn contribute to the wider system aiming to improve students' experience of learning science.

Bibliography

(2009), *Rubin Vase*. [Online]. Available at:
http://www.newworldencyclopedia.org/entry/Rubin_vase. Last accessed 3rd March 2011.

(2011), *Oxford Dictionaries Online* [Online]. Available at:
http://oxforddictionaries.com/view/entry/m_en_gb0737530#m_en_gb0737530. Last accessed 25th April 2011.

AAAS. (2001), *Atlas of science literacy*. Washington, DC: American Association for the Advancement of Science.

AAAS. (2005), *AAAS Project 2061 Textbook Evaluations*. [Online]. Available at:
<http://www.project2061.org/publications/textbook/hsbio/report/about.htm>. Last accessed 01th October 2009.

AAAS. (2009), *Habits of mind*. [Online]. Available at:
<http://www.project2061.org/publications/bsl/online/index.php?chapter=12&txtRef=&txtURIOld=%2Ftools%2Fbenchol%2Fch12%2Fch12.htm>. Last accessed 3rd March 2011.

Abrahams, I. and Millar, R. (2008), 'Does Practical Work Really Work? A study of the effectiveness of practical work as a teaching and learning method in school science'. *International Journal of Science Education*, 30 (14), 1945–1969.

Ainsworth, S. (2006), 'DeFT: A Conceptual Framework For Considering Learning with Multiple Representations'. *Learning and Instruction*, 16 (3), 183-198.

Anderson, J. R. (1983), *The architecture of cognition*. Cambridge, MA: Harvard University Press.

Anderson, J. R. (2000), *Cognitive psychology and its implications*. (5th ed.). New York: Worth Publishing.

Anderson, R. C., Kulhavy, R. and Andre, T. (1972), 'Feedback procedures in programmed instruction'. *Journal of educational psychology*, 62, 148 - 156.

Anderson, R. C., Nguyen-Jahiel, K., McNurlen, B., Archodidou, A., Kim, S., Reznitskaya, A., Tillmans, M. and Gilbert, L. (2001), 'The snowball phenomenon: Spread of ways of talking and ways of thinking across groups of children.' *Cognition and Instruction*, 19, 1-46.

Anderson, R. C., Reynolds, R. E., Schallert, D. L. and Goetz, E. T. (1977), 'Frameworks for Comprehending Discourse'. *American Educational Research Journal*, 14 (4), 367-381.

Appleton, K. (1997), 'Analysis and description of students' learning during science classes using a constructivist-based model'. *Journal of Research in Science Teaching* 34 (3), 303-318.

Arnaudin, M. W. and Mintzes, J. J. (1985), 'Students' alternative conceptions of the human circulatory system: A cross age study'. *Science Education*, 69 (5), 721-733.

Askew, M., Brown, M., Rhodes, V., Wiliam, D. and Johnson, D. (1997), 'The contribution of professional development to effectiveness in the teaching of numeracy'. *Teacher Development*, 1 (3).

Atkinson, R. and Shiffrin, R. (1968), 'Human memory: A proposed system and its control processes.' In K. Spence and J. Spence (eds), *The psychology of learning and motivation: Advances in research and theory* (Vol. 2). New York: Academic Press.

Ausubel, D. P. (1968), *Educational psychology: A cognitive view*. New York: Holt, Reinehart and Winston.

Azevedo, R., Cromley, J. G., Winters, F. I., Moos, D. C. and Greene, J. A. (2005), Adaptive human scaffolding facilitates adolescents' self-regulated learning with hypermedia, *American Educational Research Association conference*, Montreal.

Barab, S. A. and Hay, K. E. (2001), 'Doing science at the elbows of experts: Issues related to the science apprenticeship camp.' *Journal of Research in Science Teaching* 38 (1), 70-102.

Barrow, R. and Foreman-Peck, L. (2005), *The case against empirical research in education: Philosophy of Education Society of Great Britain*.

Barrows, H. S. and Tamblyn, R. M. (1980), *Problem-based learning: An approach to medical education*. New York: Springer.

Becta. (2003), *What the research says about ICT and motivation*: British Educational Communications and Technology Agency (Becta).

BECTA. (2007), *Annual Report*. Coventry.

Bell, D., Devés, R., Dyasi, H., Garza, G. F. d. I., Léna, P., Millar, R., Reiss, M., Rowell, P. and Yu, W. (2010), Principles and big ideas of science education. In W. Harlen (ed), *PURkwa seminar*. Loch Lomond.

Bell, P. and Davis, E. A. (2000), *Designing Mildred: Scaffolding Students' Reflection and Argumentation Using a Cognitive Software Guide*. Paper presented at the Fourth International Conference of the Learning Sciences, University of Michigan.

Bennett, J., Holman, J., Lubben, F., Nicolson, P. and Prior, C. (2002), *Science in context: The Salters' Approach Paper*. Paper presented at the The Second international IPNYSEG Symposium: Context-based Curricula, Kiel, Germany Bulte.

BERA. (2011), *Ethical Guidelines for Educational Research*. London: British Educational Research Association

Berthelsen, B. (1999), 'Students' naïve conceptions in life science'. *MSTA Journal*, 44 (1), 13-19.

Biological Science Curriculum Studies, B. (1993), *Developing biological literacy*. Dubuque, IA: Kendall Hunt Publishing Company.

Black, P. and Wiliam, D. (1998), *Inside the Black Box: Raising Standards Through Classroom Assessment*. (Vol. 1): NFER Nelson Publishing Co Ltd

Bloom, B. S. (1981), 'Learning for Mastery, The Evaluation Comment'. In B. S. Bloom (ed.), *All our Children Learning*. New York: McGraw Hill.

Boud, D., Keogh, R. and Walker, D. (eds) (1985), *Reflection: Turning experience into learning*. London Kogan Page.

Brandt, R. (2000), 'On teaching brains to think: A conversation with Robert Sylwester'. *Educational Leadership*, 57 (7) 72-75.

Bransford, J., Vye, N., Stevens, R., Kuhl, P., Schwartz, D., Bell, P., Meltzoff, A., Barron, B., Pea, R., Reeves, B., Roschelle, J. and Sabelli, N. (2006), 'Learning theories and education: Toward a decade of synergy'. In P. Alexander and P. Winne (eds), *Handbook of educational psychology* (2 ed.). Mahwah, NJ: Erlbaum.

Bransford, J. D., Sherwood, R. D., Hasselbring, T. S., Kinzer, C. K. and Williams, S. M. (1990), 'Anchored instruction: Why we need it and how technology can help'. In D. Nix and R. Spiro (eds), *Cognition, education and multimedia: Exploring ideas in high technology* (pp. 115-141). Hillsdale, NJ: Lawrence Erlbaum.

Bransford, J. D., Brown, A. L. and Cocking, R. R. (eds) (2000), *How people learn: Brain, mind, experience, and school* (expanded ed.). Washington, DC: National Academies Press.

Brick, B. and Holmes, J. (2008), Using screen capture software for student feedback: towards a methodology, *IADIS International Conference on Cognition and Exploratory Learning in Digital Age*. Freiburg, Germany: CELDA.

Brewer, W. and Nakamura, G. (1984), 'The nature and functions of schemas'. In R. S. Wyer and T. K. Skull (eds), *Handbook of Social Cognition* (Vol. 1). Hillsdale NJ: Lawrence Erlbaum.

Brown, J. S., Collins, A. and Duguid, P. (1989), 'Situated Cognition and the Culture of Learning'. *Educational Researcher*, 18 (1), 32-42.

Bruner, J. S. (1961), 'The act of discovery'. *Harvard Educational Review* 31 (1), 21–32.

Bruner, J. S. (1974), *Beyond the information given: studies in the psychology of knowing*. London: George Allen and Unwin.

Bruner, J. S. (1996), *The Culture of Education*. Cambridge, MA: Harvard University Press.

Bruner, J. S. (1999), *The Processes of Education*. (12th ed.). Cambridge, MA: Harvard University Press.

Brush, T. and Saye, J. (2001), 'The use of embedded scaffolds with hypermedia-supported student-centered learning'. *Journal of Educational Multimedia & Hypermedia*, 10, 333–356.

BSCS. (1993), *Developing biological literacy*. Dubuque, IA: Kendall Hunt Publishing Company.

Campbell, B., Kaunda, L., Allie, S., Buffler, A. and F. L. (2000), 'The communication of laboratory investigations by university entrants'. *Journal of Research in Science Teaching*, 37, 839–853.

Chi, M. T. H., de Leeuw, N., Chiu, M. H. and LaVancher, C. (1994), 'Eliciting self-explanations improves understanding.' *Cognitive Science*, 18, 439–477.

Collins, A., Brown, J. S. and Newman, S. E. (1989), 'Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics'. In L. B. Resnick (ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453-494). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Collins, A. and Brown, J. (1988), 'The computer as a tool for learning through reflection.' In H. Mandi and A. Lesgold (eds), *Learning issues for intelligent tutoring systems* (pp. 1–18). New York: Springer-Verlag.

Collins, A., Brown, J. S. and Holum, A. (1991), 'Cognitive Apprenticeship: Making Thinking Visible.' *American Educator*, 15 (3), 6-11.

Collins, A., Joseph, D. and Bielaczyc, K. (2004), 'Design Research: Theoretical and Methodological Issues'. *The Journal Of The Learning Sciences*, 13 (1), 15-42.

Collins, J., Hammond, M. and Wellington, J. (1997), *Teaching and Learning with Multimedia*. London: Routledge.

Conant, J. B. (1947), *On understanding science: An Historical Approach*. London: Oxford University Press.

Conole, G., Dyke, M., Oliver, M. and Seale, J. (2004), 'Mapping pedagogy and tools for effective learning design'. *Computers & Education*, 43 (1-2), 17-33.

Corrigan, D., Gunstone, R. and Dillon, J. (2011), 'Approaches to considering the professional knowledge base of science teachers'. In D. Corrigan, R. Gunstone and J. Dillon (eds), *The Professional Knowledge Base of Science Teaching* (pp. 1-11). London: Springer.

Craik, K. (1943), *The nature of exploration*. Cambridge: Cambridge University Press.

D'Andrade, R. G. (2003), *The development of cognitive anthropology*. Cambridge: Cambridge University Press.

Davis, E. A. (2004), 'Creating critique projects'. In Linn, M.C., E. A. Davis and B. Bell (eds), *Internet environments for science education* (pp. 88-113). Mahwah, NJ: Lawrence Erlbaum Associates inc.

Davis, E. A. and Linn, M. C. (2000), 'Scaffolding students' knowledge integration: Prompts for reflection in KIE.' *International Journal of Science Education*, 22, 819–837.

Davis, E. A. and Krajcik, J. S. (2005), 'Designing Educative Curriculum Materials to Promote Teacher Learning.' *Educational Researcher*, 34 (3), 3-14.

Demetriadis, S., Barbas, A., Molohides, A., Palaigeorgiou, G., Psillos, D., Vlahavas, I., Tsoukalas, I. and Pombortsis, A. (2003), 'Cultures in negotiation: teachers' acceptance/resistance

attitudes considering the infusion of technology into schools'. *Computers & Education*, 41 19-37.

Dillenbourg, P. (2002), 'Over-scripting CSCL: The risks of blending collaborative learning with instructional design'. In P. A. Kirschner (ed.), *Three worlds of CSCL. Can we support CSCL?* (pp. 61-91). Heerlen: Open Universiteit Nederland.

Dimitrov, D. M., McGee, S. and Howard, B. C. (2002), 'Changes in students' science ability produced by multimedia learning environments: Application of the linear logistic model for change.' *School Science and Mathematics*, 102, 15-24.

Directgov. (2008), *Internet Acces*. [Online]. Available at: <http://www.statistics.gov.uk/CCI/nugget.asp?ID=8>. Last accessed 16th October 2008.

de Jong, T. (2010), 'Cognitive load theory, educational research, and instructional design: some food for thought'. *Instructional Science*, 38, 105-134.

Donnelly, J. (1999), 'Interpreting differences: the educational aims of teachers of science and history, and their implications.' *Journal of Curriculum Studies*, 31 (1), 17-41.

Doolittle, R. (2003), *Moving the "sage on the stage" out of the spotlight*. Paper presented at the third annual meeting of the Future Forward Society, New York.

Draper, S. (1995), 'Computational modelling of constructive interaction: relaxing the mutuality hypothesis'. In C. O'Malley (ed.), *Computer supported collaborative learning*. Berlin: Springer Verlag

Driver, R. (1981), 'Pupils' alternative frameworks in science'. *European Journal of Science Education*, 3 (1), 93-101.

Driver, R., Asoko, H., Leach, J., Mortimer, E. and Scott, P. (1994), 'Constructing Scientific Knowledge in the Classroom'. *Educational Researcher*, 23 (7), 5-12.

Duschl, R. and Grandy, R. (2008), 'Reconsidering the character and role of inquiry in school science: Framing the debates.' In R. Duschl and R. Grandy (eds), *Teaching scientific inquiry: Recommendations for research and application* (pp. 1 – 37). Rotterdam: Sense Publishers.

Edelson, D. C., Gordin, D. N. and Pea, R. D. (1999), 'Addressing the Challenges of Inquiry-Based Learning Through Technology and Curriculum Design'. *Journal of the Learning Sciences*, 8 (3/4), 391-450.

Edelson, D. C. (2002), 'Design research: What we learn when we engage in design.' *Journal of the Learning Sciences*, 11 (1), 105-121.

Eraut, M. (2007), 'Learning from other people in the workplace'. *Oxford Review of Education*, 99 (1), 1-20.

Ericsson, K. A. and Charness, N. (1994), 'Expert performance: Its structure and acquisition'. 49, 8, 725-747.

Ewenstein, B. and Whyte, J. (2005), Knowledge practices in design: the role of visual representations as 'epistemic objects'. , *EGOS 2005, Unlocking Organisations*, Berlin, Germany: Evolution of Business knowledge.

Eylon, B. and Linn, M. (1988), 'Learning and instruction: An examination of four research perspectives in science education'. *Review of Educational Research*, 58 (3), 205-302.

Feast, L. and Melles, G. (2010, 28 June - 1 July 2010), *Epistemological Positions in Design Research: A Brief Review of the Literature*. Paper presented at the Connected 2010: 2nd International Conference on Design Education, University of New South Wales, Sydney, Australia

Fetherston, T. (2001), 'Pedagogical Challenges for the World Wide Web'. *Association for the Advancement in Computing in Education Journal*, 9 (1).

Fischler, H. (2011), 'Didaktik - An appropriate framework for the professional work of science teachers?' In D. Corrigan, R. Gunstone and J. Dillon (eds), *The Professional Knowledge Base of Science Teaching* (pp. 31-50). London: Springer.

Fisher, K. M. (1985), 'A misconception in biology: Amino acids and translation'. *Journal of Research in Science Teaching*, 22 (1), 63-72.

Fisher, W. (1989), 'Clarifying the Narrative Paradigm'. *Communication Monographs*, 56, 55-58.

Fishman, B., Marx, R., Blumenfeld, P., Krajcik, J. S. and Soloway, E. (2004), 'Creating a framework for research on systemic technology innovations'. *Journal of the Learning Sciences*, 13 (1), 43-76.

Folkestad, J. E. and Miranda, M. D. (2001), 'Impact of Screen-Capture Based Instruction on Student Comprehension of Computer Aided Design (CAD) Software Principles'. *Journal of Industrial Technology*, 18 (1), 2-7.

Frayling, C. (2006), *What is craft?* [Online]. Available at: <http://www.vam.ac.uk/content/articles/w/what-is-craft/>. Last accessed 16th July 2011.

Freebody, P. (2003), *Qualitative Research in Education*. (2nd ed.). London: Sage.

Gagné, R. M., Briggs, L. and Wagner, W. W. (1992), *Principles of Instructional Design*. (4th ed.). Fort Worth: TX: HBJ College Publishers.

Gagné, R. M. (1970), *The conditions of learning* (4th. ed). New York: Holt, Rinehart & Winston.

Gallegos, L., Jerezano, M. E. and Flores, F. (1994), 'Preconceptions and relations used by children in the construction of food chains'. *Journal of Research in Science Teaching*, 31 (3), 259-272.

Gathercole, S. E. and Alloway, T. P. (2008), *Working memory and learning: a practical guide for teachers*. London: Sage.

Geary, D. C. (2008), 'An evolutionarily informed education science'. *Educational Psychologist*, 43 179-195.

Gibbs, G. R. (2002), *Qualitative Data Analysis*. Buckingham: OUP.

Giere, R. N. (1991), *Understanding Scientific Reasoning*. (3rd ed.). Fort Worth, TX: Holt, Rinehart and Winston.

Gilbert, J. K., Osborne, R. J. and Fensham, P. J. (1982), 'Children's science and its consequences for teaching'. *Science Education*, 66 (4), 623-633.

Gilbert, J. K., Boulter, C. J. and Rutherford, M. (2000), 'Explanations with models in science education'. In J. K. Gilbert and C. J. Boulter (eds), *Developing models in science education* (pp. 3-18). Dordrecht: Kluwer.

Giordan, A. (1996), 'Learning beyond constructivism'. In A. Giordan and Y. Giralt (eds), *The new learning models: their consequences for teaching of biology, health and environment*. Nice: Z'Editions.

Giroux, H. (1992), *Border Crossings: Cultural Workers and the Politics of Education*. New York: Routledge.

Gobert, J. D. (1999), *Expertise in the comprehension of architectural plans: Contribution of representation and domain knowledge in Visual and Spatial Reasoning in Design '99* Key Centre of Design Computing and Cognition, University of Sydney, AU.

Gobert, J. D. (2005), 'Leveraging technology and cognitive theory on visualization to promote students' science.' In J. K. Gilbert (ed.), *Visualization in Science Education* (pp. 73-90). Dordrecht: Springer.

Graesser, A., Golding, J. M. and Long, D. L. (1991), 'Narrative representation and comprehension'. In R. Barr, M. L. Kamil, P. B. Mosenthal and P. D. Pearson (eds), *Handbook of reading research* (Vol. 11). New York: Longman.

Graesser, A. C., Olde, B. and Klettke, B. (2002), 'How does the mind construct and represent stories?' In M. Green, J. Strange and T. Brock (eds), *Narrative Impact: Social and Cognitive Foundations* (pp. 229-262). Mahwah, NJ: Erlbaum.

Green, H., Facer, K., Rudd, T., Dillon, P. and Humphreys, P. (2005), *Personalisation and Digital Technologies*: Futurelab.

Guba, E. G. and Lincoln, Y. S. (1994), 'Competing paradigms in qualitative research'. In N. K. Denzin and Y. S. Lincoln (eds), *Handbook of Qualitative Research*, Thousand Oaks: Sage.

Hargreaves, A. (1998), 'The emotional politics of teaching and teacher development: with implications for educational leadership'. *International Journal of Leadership in Education*, 1 (4), 315-336.

Hayakawa, S. I. and Hayakawa, A. R. (1990), *Language in Thought and Action*. (5th ed.). San Diego: Harcourt Inc.

Hegarty, M. (2004), 'Dynamic visualizations and learning: getting to the difficult questions'. *Learning and Instruction*, 14 (3), 343-351.

Hennessy, S., Wishart, J., Whitelock, D., Deaney, R., Brawn, R., Velle, L. I., McFarlane, A., Ruthven, K. and Winterbottom, M. (2007), 'Pedagogical approaches for technology-integrated science teaching'. *Computers & Education*, 48 (1), 137-152.

Herrington, J. and Oliver, R. (2000), 'An instructional design framework for authentic learning environments'. *Educational Technology Research and Development*, 48 (3), 23-48.

Hmelo-Silver, C. E., Duncan, R. G. and Chinn, C. A. (2007), 'Scaffolding and Achievement in Problem-Based and Inquiry Learning: A Response to Kirschner, Sweller, and Clark'. *Educational Psychologist*, 42 (2), 99-107.

Hodson, D. (1996), 'Laboratory work as scientific method: Three decades of confusion and distortion.' *Journal of Curriculum Studies*, 28 (2), 115 – 135.

Höffler, T. N. and Leutner, D. (2007), 'Instructional animation versus static pictures: A meta-analysis'. *Learning and Instruction*, 17 (6), 722-738.

Hogarth, S., Bennett, J., Lubben, F., Campbell, B. and Robinson, A. (2006), *ICT in Science Teaching. Technical Report*. London: EPPI-Centre, Social Science Research Unit, Institute of Education, University of London.

Holton, D. and Clark, D. (2006), 'Scaffolding and metacognition.' *International Journal of Mathematical Education in Science and Technology*, 37, 127-143.

Honebein, P. C., Duffy, T. M. and Fishman, B. J. (1993), 'Constructivism and the design of learning environments: Context and authentic activities for learning'. In T. M. Duffy, J. Lowyck and D. H. Jonassen (eds), *Designing environments for constructive learning* (pp. 87-108). Heidelberg: Springer-Verlag.

Hudson, B. (2008), 'A Didactical Design Perspective on Teacher Presence in an International Online Learning Community'. *Journal of Research in Teacher Education*, 15 (3-4), 93-112.

Hulshof, C. D. (2004), 'Log file analysis'. In L. K. Kempf (ed.), *Encyclopedia of Social Measurement* (pp. 577-583): Elsevier

IDEA. (2011), *Spicynodes*. [Online]. Available at: <http://www.spicynodes.org/index.html>. Last accessed May 27th 2011.

Imler, B. and Eichelberger, M. 'Using screen capture to study user research behavior'. *Library Hi Tech*, 29 (3), 446 - 454.

Invision. (2004), *Viewing and usability testing facilities*. [Online]. Available at: <http://www.invision-studios.co.uk>. Last accessed 5th February 2009.

ISDDE. (2011a), *Educational Designer*. [Online]. Available at: <http://www.educationaldesigner.org/>. Last accessed 29th August 2011.

ISDDE. (2011b), *International Society for Development and Design in Education* [Online]. Available at: <http://www.isdde.org>. Last accessed 29th August 2011.

Johnson, D. and Johnson, R. (1993), 'What we know about cooperative learning at the college level'. *Cooperative Learning*, 13 (3).

Johnson, D. W., Johnson, R. T. and Holubec, E. J. (1994), *Cooperative Learning in the Classroom*. VA: Association for Supervision and Curriculum Development.

Jonassen, D. (1991), 'Evaluating constructivistic learning'. *Educational Technology*, 31 (9), 28-33.

Kahneman, D. and Tversky, A. (1982), 'The simulation heuristic'. In D. Kahneman, P. Slovic and A. Tversky (eds), *Judgement under uncertainty: Heuristics and biases* (pp. 201-208). New York: Cambridge University Press.

Kalyuga, S., Chandler, P., Tuovinen, J. E. and Sweller, J. (2001), 'When problem solving is superior to studying worked examples'. *Journal of educational psychology*, 93 (3), 579-588.

Kalyuga, S., Ayres, P., Chandler, P. and Sweller, J. (2003), 'Expertise reversal effect'. *Educational Psychologist*, 38, 23-33.

Kalyuga, S. (2008), 'Relative effectiveness of animated and static diagrams: An effect of learner prior knowledge'. *Computers in Human Behavior*, 24 (3), 852-861.

Kansanen, P. (2009), 'The curious affair of pedagogical content knowledge'. *Orbis Scholae*, 3 (2), 5-18.

Kasl, E. and Elias, D. (2000), 'Creating new habits of mind in small groups'. In J. Mezirow (ed.), *Transformative adult learning*. San Francisco: Jossey-Bass.

Kelly, G. J. and Sezen, A. (2010), 'Activity, discourse and meaning'. In W.-M. Roth (ed.), *Restructuring science education*. Dordrecht: Springer.

King's College London. (2008), *Cognitive Acceleration (CASE and other projects)*. [Online]. Available at: <http://www.kcl.ac.uk/schools/sspp/education/research/projects/cognitive.html> Last accessed 29th November 2008.

Kirschner, P. A., Sweller, J. and Clark, R. E. (2006), 'Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching.' *Educational Psychologist*, 41 (2), 75-86.

Klafki, W. (2000), 'Didaktik Analysis as the Core of Preparation of Instruction'. In I. Westbury, S. Hopman and K. Riquarts (eds), *Teaching as a reflective practice. The German Didaktik tradition*. (pp. 87-107). Mawah:NJ: Lawrence Erlbaum.

Kress, G., Jewitt, C., Ogborn, J. and Tsatsarlis, C. (2001), *Multimodal teaching and learning: the rhetorics of the science classroom*. London: Continuum.

Kuhn, D., Amsel, E. and O'Loughlin, M. (1988), *The Development of Scientific Thinking Skills*. San Diego: Academic Press

Kuhn, D. (2004), 'What is scientific thinking and how does it develop?' In U. Goswami (ed.), *Blackwell handbook of childhood cognitive development* (pp. 371-393). Malden, MA: Blackwell.

Kuhn, K. (1989), 'Children and adults as intuitive scientists.' *Psychological Review*, 96, 674-689.

Latour, B. (1990), 'Drawing things together.' In M. Lynch and S. Woolgar (eds), *Representation in scientific practice* (pp. 19-68). Cambridge MA: MIT Press.

Laurillard, D. (2002), *Rethinking University Teaching: a conversational framework for the effective use of educational technology*. (2nd ed.). London and New York: Routledge.

Laurillard, D. and Ljubojevic, D. (2009), 'Evaluating learning designs through the formal representation of learning patterns'. In C. Kohls and J. Wedekind (eds), *E-Learning Patterns* (pp. 86- 05). Hershey, PA: IGI-Global.

Lave, J. (1988), *Cognition in practice*. Boston, MA: Cambridge.

Lave, J. and Wenger, E. (1991), *Situated Learning. Legitimate peripheral participation*, Cambridge: University of Cambridge Press.

Layton, D. (1973), *Science for the People*. London: George Allen & Unwin.

Leach, J. (1998), 'Teaching about the world of science in the laboratory: the influence of students' ideas'. In J. Wellington (ed.), *Practical work in school science: which way now?* London: Routledge.

Leach, J. and Scott, P. (2002), 'Designing and evaluating science teaching sequences: An approach drawing upon the concept of learning demand and a social constructivist perspective on learning'. *Studies in Science Education*, 38, 115–142.

Lemke, J. L. (1990), *Talking science: Language, learning and values*. Norwood, New Jersey: Ablex Publishing Company..

Lewalter, D. (2003), 'Cognitive strategies for learning from static and dynamic visuals. ' *Learning and Instruction*, 13, 177-189.

Lewis, J. (2004), *Salters-Nuffield Advanced Biology Evaluation. Final Report*. Leeds: Centre for Studies in Science and Mathematics Education School of Education, University of Leeds.

Lewis, J. and Kattmann, U. (2004), 'Traits, genes, particles and information: re-visiting students' understanding of genetics'. *International Journal of Science Education*, 26 (2), 195-206.

Lewis, J. (2006), 'Bringing the real world into the biology curriculum'. *Journal of Biological Education*, 40 (3), 101-106.

Li, D. D. and Lim, C. P. (2008), 'Scaffolding online historical inquiry tasks: A case study of two secondary school classrooms'. *Computers & Education* 50 (4), 1394–1410.

Lin, C.-y. and Hu, R. (2003), 'Students' Understanding of Energy Flow and Matter Cycling in the Context of the Food Chain, Photosynthesis, and Respiration. *International Journal of Science Education*, 25 (12), 1529-1544.

Linn, M. and Hsi, S. (2000), *Computers, Teachers. Peers, Science Learning Partners*. Mahwah, N.J.: Lawrence Erlbaum Associates Inc.

Linn, M. and Slotta, J. D. (2000), 'WISE science'. *Educational Leadership*, 58 (2), 29-32.

Linn, M., Davis, E. A. and Bell, P. (eds) (2004), *Internet environments for science education*. Mahwah, N.J.: Lawrence Erlbaum Associates Inc.

Loh, B., Reiser, B. J., Randinsky, J., Edelson, D. C., Gomez, L. M. and Marshall, S. (2001), 'Developing reflective inquiry practices: A case study of software, the teacher and students'. In K. Crowley, C. D. Schunn and T. Okada (eds), *Designing for science: Implications from everyday, classroom and professional settings* (pp. 279-306). Mahwah, N.J.: Lawrence Erlbaum Associates inc.

Lowe, R. K. (1990), 'Diagram information and its organisation in memory: Exploring the role of skill and experience '. *Research in Science Education*, 20 (1).

Marton, F. and Trigwell, K. (2000), 'Variatio est mater studiorum'. *Higher Education Research and Development*, 19, 381-395.

Mayer, R. (2004), 'Should there be a three-strikes rule against pure discovery learning? The case for guided methods of instruction.' *American Psychologist*, 59, 14–19.

Mayer, R. E. (1997), 'Multimedia learning: Are we asking the right questions?' *Educational Psychologist*, 32 (1), 1-19.

Mayer, R. E. and Johnson, C. I. (2008), 'Revising the redundancy principle in multimedia learning'. *Journal of Educational Psychology*, 100, 380–386.

Mayer, R. E., Mautone, P. and Prothero, W. (2002), 'Pictorial aids for learning by doing in a multimedia geology simulation game'. *Journal of Educational Psychology*, 94, 171–185.

Mayer, R. E. and Moreno, R. (2003), 'Nine ways to reduce cognitive load in multimedia learning'. *Educational Psychologist*, 38 (1), 43 - 52.

Mbajiorgu, N., Ezechi, N. and Idoko, C. (2006), 'Addressing nonscientific presuppositions in genetics using a conceptual change strategy'. *Science Education*, 91 (3), 419-438.

McKeachie, W. J. (1974), 'The decline and fall of the laws of learning'. *Educational Researcher*, 3 (3), 7 - 11.

Merriam-Webster. (2011), *Merriam-Webster Dictionary*. [Online]. Available at: <http://www.merriam-webster.com/dictionary/theory>. Last accessed 8th October 2011.

Microsoft. (2009), *Types of usability studies*. [Online]. Available at: <http://www.microsoft.com/usability/studies.mspx>. Last accessed May 30th 2011.

Miles, M. B. and Huberman, A. M. (1994), *An Expanded Sourcebook Qualitative Data Analysis*. (2nd ed.). Thousand Oaks: Sage.

Millar, R. (2004, 3-4 June 2004), *The role of practical work in the teaching and learning of science*. Paper presented at the High School Science Laboratories: Role and Vision, National Academy of Sciences, Washington D.C.

Millar, R. and Abrahams, I. (2009), 'Practical work: making it more effective'. *School Science Review*, 91 (334), 59-64.

Miller, G. A. (1956), 'The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information'. *The Psychological Review*, 63, pp. 81-97.

Monger, G. (ed.) (1986), *Nuffield Advanced Biology Study Guide II* (2 ed.): Longman.

Moreno, R., Reisslein, M. and Ozogul, G. (2009), 'Optimizing worked-example instruction in electrical engineering: The role of fading and feedback during problem-solving practice'. *Journal of Engineering Education*, 98, 83-92.

Moritz, S. (2011), *Truth and beauty*. [Online]. Available at : http://substratumseries.com/issues/truth_and_beauty/moritz_stefaner/ Last accessed May 27th 2011.

Morris, A. K. and Hiebert, J. (2011), 'Creating Shared Instructional Products : An Alternative Approach to Improving Teaching'. *Educational researcher*, 40 (5), 5-14.

Mortimer, E. and Scott, P. (2003), *Meaning Making in Secondary Science Classrooms*. Maidenhead, UK: Open University Press.

Moseley, D., Higgins, S., Bramald, R., Hardman, F., Miller, J., Mroz, M., Tse, H., Newton, D., Thompson, I., Williamson, J., Halligan, J., Bramald, S., Newton, L. and Tymms, P. (1999), *Effective Pedagogy Using ICT For Literacy and Numeracy in Primary Schools*. Newcastle: University of Newcastle.

Muller, M. J. and Czerwinski, M. (1999), 'Organizing usability work to fit the full product range'. *Communications of the ACM*, 42 (5).

Myers, M. D. (1997), 'Qualitative Research in Information Systems'. *MIS Quarterly* 21 (2), 241-242.

Nersessian, N. (2005), 'Interpreting scientific and engineering practices: Integrating the cognitive, social, and cultural dimensions.' In M. Gorman, R. D. Tweney, D. Gooding and A. Kincannon (eds), *Scientific and technological thinking* (pp. 17 – 56). Hillsdale, NJ: Erlbaum.

Newton, P., Driver, R. and Osborne, J. (2001), 'The place of argumentation in the pedagogy of school science'. *International Journal of Science Education*, 21 (5), 553 – 576.

Nicol, D. and MacFarlane-Dick, D. (2006), 'Formative assessment and self-regulated learning: A model and seven principles of good feedback practice'. *Studies in Higher Education*, 31 (2), 199-218.

Norris, C., Sullivan, T. and Poirot, J. (2003), 'No access, no use, no impact: Snapshot surveys of educational technology in K-12'. *Journal of Research on Technology in Education*, 36 (1), 15-27.

Norman, D. A. (1991), 'Cognitive artifacts'. In J. M. Carroll (ed.), *Designing interaction: Psychology at the human-computer interface* (pp. 17–38). New York: Cambridge University Press.

Norris, S. P., Guilbert, S. M., Smith, M. L., Hakimelahi, S. and Phillips, L. M. (2005), 'A theoretical framework for narrative explanation in science'. *Science Education*, 89 (4), 535–563.

OECD. (2001), *Learning to change: ICT in schools*. Paris: Organisation for economic co-operation and development.

OECD. (2006), *Assessing Scientific, Reading and Mathematical Literacy: A Framework for PISA 2006*.

Ogborn, J., Kress, G., Martins, I. and McGillicuddy, K. (1996), *Explaining science in the classroom*. Buckingham.: Open University Press.

Paas, F., Tuovinen, J. E. and Tabbers, H. (2003), 'Cognitive Load Measurement as a Means to Advance Cognitive Load Theory'. *Educational Psychologist*, 38 (1), 63-71.

Park, O-c. (1998), 'Visual displays and contextual presentations in computer-based instruction'. *Educational technology research and development*, 46 (3), 37-50.

Petre, M., Carswell, L., Price, B. and Thomas, P. (2000), 'Innovation in Large-Scale Supported Distance Teaching: Transforming for the Internet Not Just Translating'. In M. Eisenstadt and T. Vincent (ed.s), *The Knowledge Web: Learning and Collaborating on the Net* (pp. 97–117). London: Kogan Page.

O'Regan, K. (2003), 'Emotion and e-learning'. *Journal for Asynchronous Learning Networks*, 7 (3), 78-92.

Paas, F. and Sweller, J. (2012) 'An Evolutionary Upgrade of Cognitive Load Theory: Using the Human Motor System and Collaboration to Support the Learning of Complex Cognitive Tasks'. *Educational Psychology Review* (24), 27–45.

Paas, F., Tuovinen, J. E., Tabbers, H., & van Gerven, P. W. M. (2003). 'Cognitive load measurement as a means to advance cognitive load theory'. *Educational Psychologist*, (38), 63–72.

Parr, C. S., Jones, T. and Songer, N. B. (2002), *CyberTracker in BioKIDS: Customization of a PDA-based scientific data collection application for inquiry learning*. Paper presented at the Fifth International Conference of the Learning Sciences, Seattle, Washington.

Piaget, J. (1950), *The Psychology of Intelligence*. New York: Routledge.

Plowman, L., Luckin, R., Laurillard, D., Stratfold, M. and Taylor, J. (1999), Designing multimedia for learning: narrative guidance and narrative construction, *SIGCHI conference on Human factors in computing systems: the CHI is the limit*. Pittsburgh, Pennsylvania, United States: ACM.

Puntambekar, S. and Hübscher, R. (2005), 'Tools for scaffolding students in a complex learning environment: what have we gained and what have we missed?' *Educational Psychologist*, 40 (1), 1 - 12.

QCA. (2008), *Curriculum 'Big Picture'*. [Online]. Available at: [tp://www.qca.org.uk/qca_5856.aspx](http://www.qca.org.uk/qca_5856.aspx). Last accessed 27th October 2009.

Quintana, C., Reiser, B., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., Kyza, E., Edelson, D. and Soloway, E. (2004), 'A Scaffolding Design Framework for Software to Support Science Inquiry'. *Journal of the Learning Sciences*, 13 (3), 337 — 386.

Radford, M. (2006), 'Researching Classrooms; Complexity and Chaos'. *British Educational Research Journal*, 32 (2), 177 – 190.

Reeves, T. (2011), 'Can Educational Research Be Both Rigorous and Relevant?' [Online]. *Educational Designer*, 1 (4). Available at:

<http://www.educationaldesigner.org/ed/volume1/issue4/article13>. Last accessed 2nd April 2011.

Reif, F. and Scott, L. A. (1999), 'Teaching scientific thinking skills: Students and computers coaching each other'. *American Journal of Physics*, 67, 819–831.

Reiser, B., J. (2004), 'Scaffolding complex learning: The mechanisms of structuring and problematizing student work'. *The Journal of the Learning Sciences*, 13 (3), 273-304.

Reiser, B. J. (2002), *Why Scaffolding Should Sometimes Make Tasks More Difficult for Learners*. Paper presented at the Computer Supported Collaborative Learning, Boulder, CO.

Resnick, L. B. (1987), 'Learning in school and out.' *Educational Researcher*, 16 (9), 13-20.

Reynolds, R. E. and Sinatra, G. M. (2005), 'The cognitive revolution in scientific psychology: Epistemological roots and impact on reading research'. In J. M. Royer (ed.), *The cognitive revolution in educational psychology*: Information age publishing, Inc.

Rogoff, B. (1990), *Apprenticeship in thinking: Cognitive development in social context*. New York: Oxford University Press.

Rosebery, A. S., Warren, B. and Conant, F. R. (1992), 'Appropriating Scientific Discourse: Findings from Language Minority Classrooms. 'The Journal of the Learning Sciences', 2 (1), 61-94.

Royal Society of Chemistry (2009), *Discover maths for chemists*. [Online]. Available at: <http://discovermaths.rsc.org/>. Last accessed May 27th 2011.

Russell, T. L. (2001), *The no significant difference phenomenon: A comparative research annotated bibliography on technology for distance education* (5th ed.). Montgomery, AL: IDECC.

Sanders, M. (1993), 'Erroneous ideas about respiration: The teacher factor. ' *Journal of Research in Science Teaching*, 30 (8), 919-934.

Sandoval, W. A. (2003), 'Conceptual and Epistemic Aspects of Students' Scientific Explanations'. *The Journal of the Learning Sciences*, 12 (1), 5–51.

Scardamalia, M. and Bereiter, C. (1983), 'The development of evaluative, diagnostic, and remedial capabilities in children's composing.' In M. Martlew (ed.), *The psychology of written language: Developmental and educational perspectives* (pp. 67-95). London: Wiley.

Scardamalia, M. and Bereiter, C. (1985), 'Research on written composition.' In M. C. Wittrock (ed.), *Handbook of research on teaching* (3rd ed., pp. 778-803). New York: MacMillan.

Scardamalia, M. and Bereiter, C. (1987), *The psychology of written composition*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Scardamalia, M. and Bereiter, C. (1991), 'Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media.' *The Journal of the Learning Sciences*, 1 (1), 37–68.

Schauble, L., Klopfer, L. E. and Raghavan, K. (1991), 'Students' transition from an engineering model to a science model of experimentation'. *Journal of Research in Science Teaching*, 28 (9), 859–882.

Schneider, R. M., Krajcik, J., Marx, R. W. and Soloway, E. (2002), 'Performance of students in project-based science classrooms on a national measure of science achievement'. *Journal of Research in Science Teaching*, 39, 410–422.

Schnottz, W. and Kürschner, C. (2007), 'A reconsideration of cognitive load theory'. *Educational Psychology Review*, 19, 469–508.

Schoenfeld, A. H. (1987), 'What's all the fuss about metacognition?' In A. H. Schoenfeld (ed.), *Cognitive science and mathematics education* (pp. 189-215). Hillsdale, NJ: Lawrence Erlbaum Associates.

Schoenfeld, A. H. (2009), 'Bridging the Cultures of Educational Research and Design'. *Educational designer*, 1 (3).

Schönborn, K. J. and Anderson, T. R. (2006), 'The Importance of Visual Literacy in the Education of Biochemists'. *Biochemistry and molecular biology education*, 34 (2), pp. 94–102.

Schunn, C. (2008), 'Engineering Educational Design'. *Educational designer*, 1 (1).

Schwartz, D. L. and Bransford, J. D. (1998), 'A Time for Telling'. *Cognition and Instruction*, 16 (4), 475-522.

Sedighian, K., Klawe, M., & Westrom, M. (2001), 'Role of Interface Manipulation Style and Scaffolding in Cognition and Concept Learning in Learnware'. *ACM Transactions in Computer-Human Interaction*, 8 (1), 34-59.

Selley, N. J. (1989), 'Philosophies of science and their relation to scientific processes in the science curriculum'. In J. Wellington (ed.), *Skills and Processes in Science Education* (pp. 83-98). London: Routledge.

Sherin, B. (2001), 'How students understand physics equations'. *Cognition and Instruction*, 19, 459-541.

Sherin, B., Reiser, B. J. and Edelson, D. (2004), 'Scaffolding Analysis: Extending the Scaffolding Metaphor to Learning Artifacts'. *Journal of the Learning Sciences*, 13 (3), 387-421.

Shulman, L. (1986), 'Those who understand: Knowledge growth in teaching.' *Educational Researcher*, 15 (2), 4-14.

Sinclaire, M. P. (2003), 'Some implications of the results of a case study for the design of pre-constructed, dynamic geometry sketches and accompanying materials'. *Educational Studies in Mathematics*, 52 (3), 289-317.

Skinner, B. F. (1954), 'The Science of Learning and the Art of Teaching'. *Harvard Educational Review*, 24, 88 - 97.

Slavin, R. E. (1990), *Cooperative learning: Theory, research & practice*. Boston: Allyn & Bacon.

Slavin, R. E. (2002), 'Evidence-based educational policies: Transforming educational practice and research'. *Educational Researcher*, 31 (7), 15–21.

Slotta, J. D., Chi, M. T. H. and Joram, E. (1995), 'Assessing students' misclassifications of physics concepts: An ontological basis for conceptual change'. *Cognition and Instruction*, 13 (3), 373-400.

Solomon, J. (1999), 'Envisionment in practical work. Helping pupils to imagine concepts while carrying out experiments.' In J. Leach and A. Paulsen (eds), *Practical work in science education: Recent research studies* (pp. 60–74). Roskilde, The Netherlands: Roskilde University Press.

Solomon, J. (2002), 'Science Stories and Science Texts: What can they do for our students?' *Studies in Science Education*, 37 (1).

Spektor-Levy, O., Eylon, B.-S. and Scherz, Z. (2008), 'Teaching communication skills in science: Tracing teacher change'. *Teaching and Teacher Education*, 24 (2), 462-477.

Sutton, C. R. (1992), *Words, Science and Learning*. Buckingham Open University Press.

Swan, M. (2008), 'Designing a Multiple Representation Learning Experience in Secondary Algebra'. *Educational designer*, 1 (4), 1-17.

Sweller, J. (1988), 'Cognitive load during problem solving: Effects on learning'. *Cognitive Science: A Multidisciplinary Journal*, 12 (2), Pages 257-285.

Sweller, J. and Chandler. (1994), 'Why some material is difficult to learn'. *Cognition and Instruction*, 12 (3), 185-233.

Sweller, J., Van Merriënboer, J. and Paas, F. (1998), 'Cognitive architecture and instructional design'. *Educational Psychology Review*, 10, 251–296.

Tamir, P. (1991), 'Professional and personal knowledge of teachers and teacher educators'. *Teaching and Teacher Education*, 7 (3), 263-268

TechSmith. (2007), *Rich Recording Technology : Digitally Synchronizing Data from People and Systems*: TechSmith Corporation.

ten Have, P. (1999), *Doing conversation analysis: a practical guide*. London: Sage.

Thompson, C. L. and Zeuli, J. S. (1999), 'The frame and the tapestry'. In L. Darling-Hammond and G. Sykes (ed.s), *Teaching as the Learning Profession: Handbook of Policy and Practice* (pp. 341-375). San Francisco, CA Jossey-Bass.

Tiberghien, A. (2000), 'Designing teaching situations in the secondary school.' In R. Millar, J. Leach and J. Osborne (ed.s), *Improving science education: the contribution of research* (pp. 27–47.). Buckingham: Open University Press.

Tort, F., Blondel, F.-M. and Bruillard, É. (2009), *From error detection to behaviour observation: first results from screen capture analysis*. Paper presented at the The European Spreadsheet Risks Interest group

Tsay, M. and Brady, M. (2010), 'A case study of cooperative learning and communication pedagogy: Does working in teams make a difference?' *Journal of the Scholarship of Teaching and Learning*, 10 (2), 78 – 89.

Tversky, B., Morrison, J. B. and Betrancourt, M. (2002), 'Animation: Can it facilitate? ' *International Journal of Human–Computer Studies*, 57, 1–16.

UNFLASH. (2002), *ScreenFlash*. [Online]. Available at: <http://unflash.com/>. Last accessed 6th February 2009.

Van Merriënboer, J. J. G. and Sweller, J. (2005), 'Cognitive load theory and complex learning: recent developments and future directions.' *Educational Psychology Review*, 17, 147-177.

VanLehn, K. (1989), 'Problem solving and cognitive skill acquisition '. In M. Posner (ed.), *Foundations of cognitive science* (pp. 527-580). Cambridge, MA: Harvard University Press.

Venville, G., Gribble, S. and Donovan, J. (2004), 'An exploration of young children's understandings of genetics concepts from ontological and epistemological perspectives.' *Science Education*, 89 (4), 614-633.

Voss, J. F., Wiley, J. and Sandak, R. (1999), 'On the use of narrative as argument. ' In S. R. Goldman, A. C. Graesser and P. V. D. Broek (ed.s), *Narrative comprehension, causality, and coherence: Essays in honor of Tom Trabasso*. Mahwah, NJ: Lawrence Erlbaum.

Voss, J. L., Gonsalves, B. D., Federmeier, K. D., Tranel, D. and Cohen, N. J. (2011), 'Hippocampal brain-network coordination during volitional exploratory behavior enhances learning'. *Nature Neuroscience*, 14 (1), 115–120.

Vygotsky, L. S. (1962), *Thought and language*. Cambridge, MA: The MIT Press.

Vygotsky, L. S. (1978), *Mind in Society*. Cambridge, MA: Harvard University Press.

Vygotsky, L. S. (1987), 'Speech and Thinking'. In R. Rieber and A. Carton (eds), *L.S. Vygotsky, Collected Works* (Vol. 1, pp. 39-285). New York: Plenum.

Wales, T. and Robertson, P. 'Captivating Open University students with online literature search tutorials created using screen capture software '. *Program Electronic Library And Information Systems* 42 (4).

Wandersee, J. H., Fisher, K. M. and Moody, D. E. (2000), 'The nature of biology knowledge.' In K. M. Fisher, J. H. Wandersee and D. E. Moody (eds), *Mapping biology knowledge* (pp. 25 – 37). Dordrecht: Kluwer.

Watson, D. M. (1998), 'Blame the technocentric artifact! What research tells us about problems inhibiting teacher use of IT'. In G. Marshall and M. Ruohonen (ed.s), *Capacity Building for IT in Education in Developing Countries* (pp. 185-192). London: Chapman & Hall.

Weber, R. J. (2006), The Wright Brothers and the Heuristics of Invention, *Expertise in Context* Conference, Humboldt University, Berlin, Germany.

Wellington, J. and Osborne, J. (2001), *Language and literacy in science education*. Philadelphia, USA: Open University Press.

Wells, G. (2008), 'Learning to use scientific concepts.' *Cultural Studies of Science Education*, 3 (2), 329–350.

Westbury, I. (2000), 'Teaching as a reflective practice: what might Didaktik teach Curriculum?'. In I. Westbury, S. Hopman and K. Riquarts (ed.s), *Teaching as a Reflective Practice: The German Didaktik Tradition*. (pp. 15-40). Mawah: NJ Lawrence Erlbaum.

White, B. (1984), 'Designing Computer Games to Help Physics Students Understand Newton's Laws of Motion'. *Cognition and Instruction*, 1 (1), 69-108.

White, R. (1994), 'Dimensions of content.' In P. Fensham, R. Gunstone and R. White (ed.s), *The content of science: A constructivist approach to its teaching and learning* (pp. 255– 262). London The Falmer Press.

Wiggins, G. and McTighe, J. (1999), *Understanding by Design*. Alexandria, VA: Association for Supervision and Curriculum Development.

Windschitl, M., Thompson, J. and Braaten, M. (2008), 'Beyond the scientific method: Model based inquiry as a new paradigm of preference for school science investigations.' *Science Education*, 92 (5), 941-967.

Wood, D. J., Bruner, J. S. and Ross, G. (1976), 'The role of tutoring in problem solving.' *Journal of Child Psychiatry and Psychology*, 17 (2), 89-100.

Woodrow, J. E. (1992), 'Locus of control and student teacher computer attitudes.' *Computers & Education*, 14 (5), 421-432.

Yelland, N. and Masters, J. (2007), 'Rethinking scaffolding in the information age.' *Computers & Education*, 48 (3), 362-382.

Zhang, M. and Quintana, C. (2012). 'Scaffolding strategies for supporting middle school students' online inquiry processes.' *Computers & Education*. 58. (1) 181–196.

Appendix I Pre-tutorial test

1 What is a gene?

2 Where would you find genes in a plant or animal cell?

3 Explain how genes affect processes taking place in the cell.

4 Suggest how a gene might influence the development of a remote part of the cell, for example the shape of the cell, or amount of folding of the cell membrane.

Appendix 2 Post-tutorial test

1 Explain how genes affect processes taking place in the cell.

2 Suggest how a gene might influence the development of a remote part of the cell, for example the shape of the cell, or amount of folding of the cell membrane.

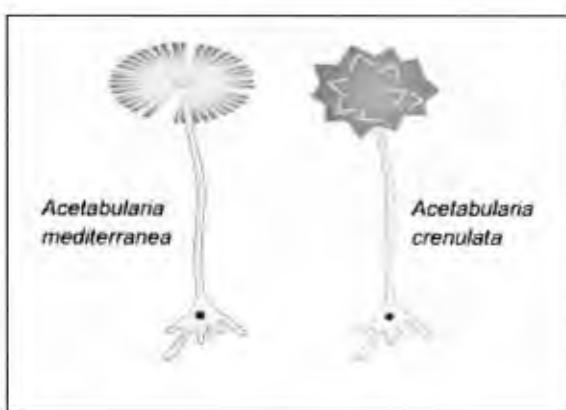
3 Summarise one or more conclusions that you think can be drawn from each of the four *Acetabularia* experiments. Write your conclusions into the table below. For each statement that you write into the conclusion column, you should write the precise evidence from the experiment which supports your conclusion. You may write the same conclusion for more than one experiment.

One example is given for you.

Experiment number	Conclusion	Supporting evidence
1	The stem does not contain genetic material. <i>You add another conclusion for experiment 1 if you can</i>	The stem doesn't grow a new hat or a new rhizoid.
2		
3		
4		

Appendix 3 Paper activity question 6

Q6. This question is to be carried out individually. There are two species of *Acetabularia*, *Acetabularia mediterranea* and *Acetabularia crenulata*. These two species have different shaped hats.



Design an experiment to test the hypothesis that it is the nucleus which controls development of the cell, using information you have learned about in Experiments 1 – 3 on *Acetabularia*.

Spend 5 -10 minutes discussing this, then draw or write out the stages of the experiment, for example as a flow chart.

Appendix 4 Paper activity question 8

Q8. Summarise the conclusions that can be drawn from the four *Acetabularia* experiments in the table below. For each statement that you write into the conclusion column, you should state the precise evidence from one or more of the experiments. If there is another piece of evidence which conflicts with the conclusion, you should write this in the last column.

An example is given:

Conclusion	Supporting evidence	Conflicting evidence
1. All the genetic material is contained in the rhizoid.	Experiment 1: The rhizoid is the only section which develops into a complete plant. Experiment 4: The new hats that eventually develop correspond to the species of <i>Acetabularia</i> of the rhizoid.	Experiment 1: Some genetic material could be in the tip, as the tip can develop a hat even when the rhizoid is cut off.
2.		

Appendix 5 Permission letters for the study

Science Learning Centre London,
Institute of Education,
20, Bedford Way,
London WC1H 0AL

Tel: 020 7612 6325
Fax: 020 7612 6792

www.sciencelearningcentres.org.uk

01 March 2006

Dear Parent or Guardian,

This is to inform you about a request that has been passed to your son or daughter, which they agreed to, asking them if they would be prepared to take part in a research project. A copy of the letter they have received is below. If you have any queries about this letter, please contact me on 020 7612 6325 angela.hall@ioe.ac.uk, or alternatively contact the Head of Biology, Hilary Thomson 020 8835 2530 to discuss this further.

Yours sincerely



Dear Student,

I am part of the project team developing Salters-Nuffield Advanced Biology, working at the Nuffield Curriculum Centre. I am currently revising the A2 materials, in light of comments from pilot school teachers and students. I was involved in the development of the AS ICT tutorials that your son or daughter are currently using in your advanced biology course.

I am interested in how this software helps students learn. With your consent, I would like to carry out a study at [REDACTED] using your advanced biology teaching group.

I will explain the procedure for my study fully when I attend your biology lesson, before you give final agreement to taking part. Briefly, it will involve you carrying out a SNAB tutorial, and being recorded. I will give you a short test before and after carrying out the tutorial, to find out what you have learned.

I would also like to interview some students later, about their use of the tutorial.

Any data collected will be completely anonymous. This means that your teachers, parents and friends will not be able to link any data with your name. I am the only person who will be aware of which student provided each set of data. The data will be in the form of an audio recording, and a Screen Flash (video) recording of what is happening on your computer screen. I will also

collect some personal information, including your name, gender, what you are studying and your GCSE results.

The study will not interfere with how you learn from the activity, it should be a genuine learning experience.

I will give you another opportunity to consent to being part of the study when I come to [REDACTED], and you can withdraw from the study at any stage, if you wish. At this stage I will ask you to give consent for the anonymised data to be used in possible future publications about my research.

This type of research is helpful for future software developments, so I will be extremely grateful to be able to work with you in this way.

If you agree to take part in this study in principle, please sign the form below, then return the form to your teacher. If you wish to find out more about this research, please ask your teacher or call or email me on 020 7612 6325 angela.hall@ioe.ac.uk.

Yours sincerely

AM Hall

.....

I agree in principle to take part in the study described above. I understand that any data collected will be anonymous. I understand that I will have an opportunity to learn more about the research study before finally consenting to taking part. I understand that the data collected may be used in publications about the study.

Student Name (block capitals)

.....
Signature

.....
Date

Appendix 6 Supporting evidence for learning background science idea

Data category from task model	Main source (s) of evidence	Examples as a proportion of the sample	Selected examples	Inferences from the data
<i>1. Cells contain specialised structures</i>				
Knowledge of the nucleus as a structure.	Written answers to Question 6. Centre A.	All 10 students represented the nucleus in their experiment plans, and referred to transferring the nucleus between two individuals or to different parts of an <i>Acetabularia</i> cell.	<p>“... See where regrowth has occurred. It is always from the rhizoid or from the section where the nucleus is present”. [FF]</p> <p>“... place stem with no nuclei into cultured dish and observe for growth”. [LF]</p>	Students have knowledge of the nucleus.
<i>2. The nucleus contains the cell's genetic material</i>				
The genetic material is in the nucleus.	Written Question 8 questions from both centres.	41/47 students included a written conclusion which directly stated that the nucleus containing the genetic material (Centre A students were also able to refer to evidence from	<p>“All genetic material is contained in the nucleus”. [DF]</p> <p>“All the genetic material is contained in the nuclei”. [LF]</p> <p>“All genetic material is</p>	<p>Students understand that the nucleus contains the cell's genetic material.</p> <p>Students were able to restate prior learning about the nucleus to the</p>

	earlier experiments that suggests the stem contains genetic material).	contained in the nuculus". [EF] "Nucleus contains genetic material not rhizoid". [EN]	new context of <i>Acetabularia</i> .
3. The genetic material contains the code which determines which proteins are made in the cytoplasm.			<p>There is confusion about what the controlling material in the cytoplasm is.</p> <p>"The nucleus contains the information for the production of the cell but some genetic material is stored in the cytoplasm + chemically transported to the tip".</p> <p>"Genetic information is contained in the stem but the info from the nucleus eventually takes over".</p> <p>"The stem contains genetic material but its mainly the nucleus".</p>

<p>3. The genetic material contains the code which determines which proteins are made in the cytoplasm.</p>	<p>Knowledge of the nucleus as a structure.</p>	<p>Students have knowledge of the nucleus.</p> <p>“.... see where regrowth has occurred. It is always from the rhizoid or from the section where the nucleus is present”. [F]</p> <p>“... place stem with no nuclei into cultured dish and observe for growth”. [L]</p>
<p>Written answers to Question 6. Centre A.</p>	<p>All 10 students represented the nucleus in their experiment plans, and referred to transferring the nucleus between two individuals or to different parts of an <i>Acetabularia</i> cell.</p>	<p>A gene codes for a particular amino acid which codes for a particular protein which has a certain shape.”</p> <p>“It will code for a specific amino acid chain ...”</p> <p>“... the codons code for different amino acids which make up different proteins. The genes create chemical signals in the cytoplasm which then travel about the cell ...”</p>
<p>There is a link between the genetic code and chemicals in the cytoplasm.</p>	<p>Post-tutorial tests from Centre B.</p>	<p>When describing how genes might affect development, 8/37 students refer directly to the link between the genetic code and proteins made in the cytoplasm.</p>

<p>Transcription and translation or protein synthesis are involved in development of a new hat in <i>Acetabularia</i>.</p>	<p>Post-tutorial tests from Centre B.</p> <p>12/37 students (including the 8 above) indicate that transcription and translation or protein synthesis are involved in development of a new hat in <i>Acetabularia</i>.</p>	<p>“DNA transcribes into mRNA which send messages to different parts of the cell...”</p> <p>“They determine the proteins made”.</p>	<p>Less than one third of the students make the link between transcription and translation or protein synthesis and development in <i>Acetabularia</i>.</p>
<p>4. Chemicals in the cytoplasm control the cell's activities</p>	<p></p>	<p></p>	<p></p>
<p>The nucleus controls the cell's activities.</p>	<p>Written answers to Questions 6 from Centre A and Question 8 from both centres.</p>	<p>All students (54) provide a written reference to control by the nucleus in some form.</p>	<p>Students understand that the nucleus exerts control over the cell's activities.</p>
<p>The nucleus controls the cell's activities.</p>	<p>Post-tutorial tests from Centre B</p>	<p>35/37 students referred to control of cell activities by the nucleus in some form.</p>	<p>Students understand that the nucleus exerts control over the cell's activities.</p>
<p>There are controlling chemicals present in the cytoplasm</p>	<p>Post-tutorial tests from Centre B</p>	<p>13/37 students mention controlling 'chemicals' in the cytoplasm. They refer to these as 'information'</p>	<p>Around half the students are aware that chemicals in the cytoplasm exert</p>

<p>(1), 'messages' (2), 'chemical signals' (3), 'chemicals/ chemical information' (2) and 'chemical reaction' (1).</p> <p>In addition, 7 students refer to genes or genetic material being present in the cytoplasm: 'chromosomes transported chemically' (2), 'genes/genetic material' move into the cytoplasm (5).</p>	<p>" cytoplasm....."</p> <p>" ... chromosomes are transported chemically through an organism..."</p>	<p>" cytoplasm....."</p> <p>" ... chromosomes are transported chemically through an organism..."</p>	<p>control on cell processes.</p>
<p>5. Development of characteristics is controlled by chemicals in the cytoplasm.</p>	<p>Written answers to Question 6 from Centre A.</p>	<p>All 10 students showed they understood their planned experiment was about seeing the effect on development of moving the nucleus to different parts of the cell, or to a different cell.</p>	<p>Students appreciate the link between the nucleus and development.</p> <p>" ... 2. remove nucleus from both plants 3. Insert AC nucleus in AM plants and viceversa. 4. Put them in petri dishes and see what hats they grow". [F]</p> <p>" ... we will see if the nucleus creates a hat corresponding to its species in the new plant</p>
<p>The nucleus is necessary for development.</p>			

There is a link between the chemicals in the cytoplasm and development.	Written question 8 from Centre A and similar question from Post-tutorial test in Centre B.	28/47 students refer to presence of controlling chemicals in the stem or cytoplasm. In some cases this is referred to as genetic material, along with 'information', 'messages' and 'enzymes'.	“... chemicals can be stored in the stem to develop a new hat”. “Genetic information is chemically sent from the nucleus into the cell. The stem grows a hat.”	Up to half of the students students make the link the between chemicals in the cytoplasm and development of the cell.
There is a link between the chemicals in the cytoplasm and development.	Post-tutorial tests from Centre B.	10/37 students referred directly to chemicals in the cytoplasm directly influencing development of the cell.	“... The nucleus sends a message to the tip. When it's cut off, enzymes in the tip are still present. The stem grew a hat.”	“... certain genes can send chemicals to influence the shape of a cell ...” “... the shape and folding of the membrane would be affected by signals in the cytoplasm ...”
There is a link between the chemicals in the cytoplasm and development.	Post-tutorial tests from Centre B.	There is evidence of misconceptions about where the genetic material is in the cell.	“... chromosomes are chemically transported through an organism, and depending on which genes replicate, decides the overall shape.”	There is a range of different types of misconceptions in the post-tutorial tests.
There is a link between the chemicals in the	Post-tutorial interviews from	1/8 students showed confusion about where the genetic material is in their	“... what happened was the rhizoid with the nucleus from the other plant, when attach,	Misconceptions led from students' interpretations of Experiment 4. The idea

cytoplasm and development.	Centre A.	Post-tutorial interpretation of Experiment 4.	when got on to the stem of the other plant, grew its original flower, which shows that there is a bit of genetic material in the rhizoid ...	that genetic material might be in different parts of the cell emerged from this experiment.
Transcription and translation or protein synthesis are involved in development of a new hat in <i>Acetabularia</i> .	Post tutorial interviews.	Without prompting, none of the students interviewed could tell the complete story of development in <i>Acetabularia</i> drawing on prior knowledge.	<p>“... and that was basically showing that the tip had some of the um like DNA able to produce a hat.” [FF describing Experiment 1 in the post-tutorial interview]</p> <p>“... how can something that's a long way away control that hat?</p> <p>By something sending.</p> <p>Sending what?</p>	Students do not resituate knowledge and understanding of transcription and translation to explain development in <i>Acetabularia</i> .
Transcription and translation or protein synthesis are involved in development of a new hat in <i>Acetabularia</i> .	Comparing the pre- and post-tutorial test responses.	Of the 12 students from Centre B who produced a pre-test explanation of the role of genes in development using a description of protein synthesis, 4 produced post-tutorial test answers which were less sophisticated or more confused.	<p>“... (gene) controls codes which control processes (development) in a cell ...” in the pre-tutorial test then no answer at all in the post-tutorial test.</p> <p>Another student:</p> <p>“... different genes have different sequences of bases which code for the amino acids used to make the</p>	<p>The answer in the post-tutorial test emphasises the conclusions of the experiments rather than the causal mechanism asked for in the question, and provided in the pre-test. It demonstrates an inability to resituate the prior learning which could provide an explanatory mechanism for the Hammerling experiments.</p>

	<p>account of transcription and translation in the pre-test answered the same question in the post-tutorial test without referring to protein synthesis.</p>	<p>proteins , and affects what cell is being made and its purpose...." in the pre-tutorial test becomes "the codons code for different amino acids which make up different proteins. The genes create chemical signals in the cytoplasm which then travels about the cell..."</p>	<p>In this case the new knowledge appears to have displaced the old rather than building on it.</p> <p>The third example on the left implies this student sees the chemical signals referred to in the tutorial as something separate from the protein synthesis she already knew about.</p>
--	--	---	--

Appendix 7 Supporting evidence for learning contextual science ideas

Data category from task model	Main source (s) of evidence	Examples as a proportion of the sample	Selected examples	Inferences from the data
<p>I. Acetabularia is a single cell with specialised parts (hat, stem and rhizoid).</p>	<p>See also Background science point 5. For misconceptions about what <i>Acetabularia</i> is.</p>		<p>“... it's already in order. Isn't it? Oh is it?</p> <p>That'll be the tip. Yes it doesn't have a head yet ...” [LF and DM screen 4]</p> <p>“... just click on it and click on the stem.” [FF screen 18]</p> <p>“... but we put the nucleus inside the thing, the stem, didn't we?” [DM screen 2]</p> <p>So that's the ac-et ab-bubba that has the nucleus [LM refers to the visual of experiment]</p>	<p>LF and DM discuss dragging all three sections of <i>Acetabularia</i> to the Petri dishes. FF refers to moving the nucleus into the stem.</p> <p>These utterances also provide evidence that the visuals stimulate articulation and reflection.</p>
<p>Students refer to specialised structures of <i>Acetabularia</i>.</p>	<p>Transcripts of discussions as students carry out the tasks on the screens.</p>	<p>All three recorded pairs made reference to the specialised parts of the <i>Acetabularia</i> cell.</p>	<p>“... it's already in order. Isn't it? Oh is it?</p> <p>That'll be the tip. Yes it doesn't have a head yet ...” [LF and DM screen 4]</p> <p>“... just click on it and click on the stem.” [FF screen 18]</p> <p>“... but we put the nucleus inside the thing, the stem, didn't we?” [DM screen 2]</p> <p>So that's the ac-et ab-bubba that has the nucleus [LM refers to the visual of experiment]</p>	<p>Students show they</p>
<p>Students refer to</p>	<p>Transcripts of</p>	<p>Each of the four recorded</p>	<p>“What's the rhizoid? like the</p>	<p>Students show they</p>

<p>specialised structures of <i>Acetabularia</i>.</p> <p>discussions as students carry out the tasks on the screens.</p>	<p>pairs of students struggle with terms at some point in their discussion of the tutorial tasks.</p> <p>Written answers to Question 6, Centre A.</p> <p>7/10 students referred to 'hat'</p> <p>8/10 referred to 'stem'</p> <p>3/10 referred to 'tip'</p> <p>6/10 referred to 'rhizoid'</p> <p>10/10 referred to 'nucleus'</p>	<p>"But the thing grew before then it didn't have the nucleus, didn't it?" [F screen 2], referring to the hat which grows in an earlier experiment]</p> <p>"...cut the cell into its 3 sections, tip, stem and rhizoid" [FF]</p> <p>"remove tip and rhizoid from stem" [LF]</p> <p>"... well how are you going to reattach the rhizoid?" [FF experiment planning, Question 6]</p>	<p>By this stage in the tutorial, students are familiar with the names of the parts of <i>Acetabularia</i> and can use these in context.</p> <p>By the end of the tutorial students can use names of parts of <i>Acetabularia</i> confidently.</p> <p>"It was the hat which corresponded to the nucleus present which grew." [FF]</p> <p>"The rhizoid does not control the development of the complete cell but nucleus does."</p> <p>44 refer to 'nucleus'</p> <p>37 refer to 'tip'</p>	<p>There is still some confusion about what <i>Acetabularia</i> is by the time students carry out Question</p>
<p>Students refer to specialised structures of <i>Acetabularia</i>.</p>	<p>Written answers to Question 8, both centres.</p>	<p>/47 written answers:</p> <p>44 refer to 'rhizoid'</p> <p>47 refer to 'hat'</p> <p>44 refer to 'stem'</p>	<p>/10 students:</p> <p>I refers to all of 'cell', species name and 'plant'</p>	<p>"Remove rhizoids from rest of cell." [LF]</p> <p>"the nucleus controls</p>
<p>Students refer to <i>Acetabularia</i> as a 'cell', 'plant' and 'alga'.</p>	<p>Question 6 written answers Centre A.</p>	<p>"Remove rhizoids from rest of cell." [LF]</p>	<p>"the nucleus controls</p>	

				6.

<p>'plant' and 'alga'.</p>	<p>relationship between the control by the nucleus and development of specialised parts of a multicellular plant.</p> <p>"A gene may be included into the nucleus which would send out chemical signals to different cells influencing the development of a remote part. For example, in a plant the stem may produce a new 'head' hat due to the chemical signal from the nucleus containing the genes."</p>	<p>therefore if a vital part of a plant is damaged it should grow back."</p>
<p>Students refer to <i>Acetabularia</i> as a 'cell', 'plant' and 'alga'.</p>	<p>Post-tutorial interviews.</p>	<p>"... they took the nucleus out of the green plant and put it in the red plant." [AM describing Experiment 4]</p> <p>"... they had two different plants." [HF describing Experiment 4]</p> <p>"... he cut the end of the nucleus off of two different types of alga." [DF describing Experiment 4]</p> <p>"... and the stem grew a complete cell." [EF describing Experiment 3]</p> <p>Students alternate between referring to <i>Acetabularia</i> as a cell, plant and alga in the post-tutorial interviews.</p>

<p>2. <i>Acetabularia</i> is ideal for this type of inquiry, because it is large enough to dissect and manipulate.</p>	<p>Written answers to Question 6.</p>	<p>10 experiment plans.</p>	<p>See Appendix 9 and Appendix 10 scanned experiment plans.</p>	<p>Students' plans show evidence of using the techniques of cell dissection and nuclear transfer.</p> <p>IF and her partner use the second species to run a repeat experiment rather than swapping parts between the species, but IF demonstrates familiarity with the process of Hammerling's inquiry (Appendix 9).</p> <p>EF and her partner produce a more sophisticated plan, where the nuclei are swapped between the two species of <i>Acetabularia</i> to see if they develop different shaped hats (Appendix 9).</p> <p>The plans produced for Question 6 demonstrate an understanding of the process of setting</p>
---	---------------------------------------	-----------------------------	---	--

		up an experiment to test a hypothesis, and the way that <i>Acetabularia</i> can be used for this inquiry.
3. A complete cell develops from any cell part that has the nucleus present, or from parts to which the rhizoid containing the nucleus has remained attached after removal of the hat.	See written evidence under Appendix 6 , Background science ideas Point 4.	Students are aware that the rhizoid or nucleus must be present for the cell to develop fully.
	Question 8 written answers from both centres.	"the genetic material comes from the rhizoid". "hat same as rhizoid"
	35/47 students referred to the controlling role of the rhizoid, using evidence from Hammerling's earlier experiments to back up their conclusions.	Students understand the inferences for Hammerling's early experiments, that the rhizoid has an influence on development in <i>Acetabularia</i> .

<p>4. A chemical signal travels between the nucleus and the cytoplasm, and these chemicals in the cytoplasm determine development of the cell parts.</p>	<p>The evidence for this has already been described under point 5 of the Appendix 6 Background science ideas.</p>		

Appendix 8 Supporting evidence for learning scientific inquiry processes

Data category from task model	Main source (s) of evidence	Examples as a proportion of the sample	Selected examples	Inferences from the data
1. Analyzing data (observations)				
Observing and summarising the processes and outcomes of an experiment.	Transcripts.	The transcripts all show examples where students make references to the experimental processes and outcomes shown in the animations of the experiments in the tutorial.	<p>“... they’re both the same.” [EF screen 26]</p> <p>“... they grow into the same thing.” [LF screen 26]</p> <p>“In experiment one he cut it into three bits and he had the um the tip the stem and the bit containing the nucleus and he put them into separate um Petri dishes and watched what happened...” [DF post-tutorial discussion].</p>	These utterances also provide evidence that the animations stimulate articulation and reflection.

			and manipulate).
2. Constructing explanations.			
Students apply their understanding of the experiments.	Transcripts of discussion during Question 6.	Students have to engage with the inquiry question as they plan their own experiment in Question 6.	<p>"Are we doing it on both of them, or just the new one, the one with the crenulata? we must do it or it would n't work."</p> <p>"... we just like leave that one to grow and we see if it grows or not without the nucleus. And then cut it from there again, and leave it with a nucleus and see if it grows to a full one. And the same with this one as well."</p> <p>"... you can see if it can grow like the you know forgotten what it's called the bit at the bottom".</p> <p>"... but you'd use that one to see if. You'd do that to see if it like applied to other species."</p> <p>"... we're trying to see if it grows to a whole new one without the nucleus or not".</p>

<p>Students form inferences from the data.</p>	<p>predictive models.</p> <p>“... take the nucleus out of it and see if it grows properly or not?”</p> <p>“... and we just like leave that one to grow and we see if it grows or not without the nucleus.”</p>	<p>bit of the stem, didn't it?”</p> <p>“... take the nucleus out of it and see if it grows properly or not?”</p> <p>“... and we just like leave that one to grow and we see if it grows or not without the nucleus.”</p>	<p>out and why any interventions might lead to useful data.</p> <p>The discussions of Experiment 4 are richer than discussions of the previous experiments. There is the suggestion that students are interested in the outcomes because they have planned their own experiment.</p> <p>“... we were kind of right no we were n't</p> <p>I told you you could switch the stems ...</p> <p>“... they grow into the same thing...”</p> <p>“... they're both the same wooww ...”</p> <p>“... they grew the type of hat of its nucleus, so that showed that um the genetic information of the cell is</p>
<p>Students form inferences from the data.</p>	<p>Post-tutorial interviews.</p>	<p>The post-tutorial interviews provide evidence of students'</p>	<p>The post-tutorial interviews provide evidence of students'</p>

<p>data.</p>	<p>Students critique provided conclusions in relation to the data.</p>	<p>Transcripts of discussion associated with carrying out the multiple choice questions.</p>	<p>“... the rhizoid had the nucleus so it had all the DNA needed for a cell and the stem didn't have any so it couldn't regrow at all.” [FF]</p> <p>“... the end of the first one didn't actually have a bottom bit but it still grew a hat.”</p> <p>“Oh no. What d'you reckon? Cos it grew a hat both times, didn't it? Oh no. Oh no actually I s'pose. Cos like in the first one there was like just the stem bit and it didn't grow anything, did it?”</p>	<p>explanations at the level of simple inferences.</p> <p>Students reason about the conclusions provided in the multiple choice questions.</p> <p>The conclusion “All the generic material is contained in the nuclei” is supported by evidence “Experiment 3: the stem that contained the nuclei from the rhizoid grew into a complete new cell”, and “Experiment 4: the hats that are developed corresponds to the nuclei that is present” [LF written answer Question 8].</p> <p>“Chemicals can be stored in stem to develop new hat” is supported by “Experiment 4: Rhizoid was swapped species but new hat corresponding to the stem species” [EM written answer Question 8].</p> <p>“The nucleus controls development</p>
---------------------	---	---	---	--

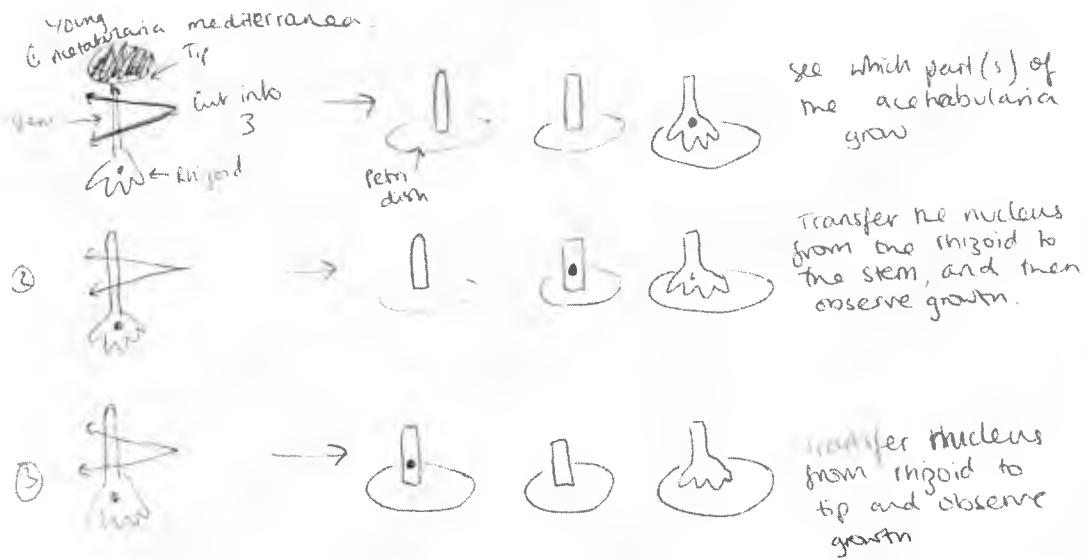
<p>Students can form simple conclusions supported by evidence.</p>	<p>Pre-test from both centres.</p> <p>Twelve explanations in terms of the genes affecting the structure of proteins.</p> <p>Sixteen explanations in terms of genes containing information which affects cell processes.</p> <p>Two explanations in terms of inheritance.</p> <p>Two explanations in terms of the transcription and translation.</p>	<p>"Experiment 4: the stems and rhizoids are switched between 2 species. The eventual hats that develop correspond to the species of nucleus" [F written answer Question 8].</p> <p>"The order of the code affects the tertiary structure ..."</p> <p>"... it contains codes which affect cell processes..."</p> <p>"... the gene may have a mutation attached to a gene from a parent ..."</p> <p>"... the information is then translated on a ribosome."</p> <p>10/37 responses were constructed as evidence plus explanation.</p>	<p>Before carrying out the tutorial, students do not provide explanations for development in terms of evidence.</p>
--	---	--	---

	<p>“... a gene may be included into the nucleus which would sent out chemical signals to different cells influencing the development of a remote part. For example, in a plant, the stem may produce a new head/ hat due to the chemical signal from the nucleus containing the genes.”</p> <p>“The gene in the nucleus control development of the cell. For example the stem won't control the development unless the nucleus has been transferred to the stem”.</p>	<p>The complexity of the multiple choice questions appears to cause confusion.</p>
<p>Students can form simple conclusions supported by evidence.</p>	<p>Transcripts of students carrying out multiple choice questions.</p> <p>“...the last one is like just Experiment I didn't even have anything to do with it. Sort of it wasn't involved...” [FF screen 12]</p> <p>“... oh God I really don't know this time...” [FF screen 13]</p> <p>“... the second last two mean exactly the same.” [FF trying to distinguish between two of the optional answers on screen 12]</p>	<p>EF and DF discuss the question on screen 12 with three optional answers. The first incorrect submission and feedback does not promote any reflection on why the</p>
<p>Students can form simple conclusions supported by evidence</p>	<p>Transcripts of responses to feedback from multiple choice questions.</p>	<p>“... Experiment 2. What d'you think?</p> <p>..... wait a sec. I think it's that one</p> <p>Yea</p>

<p>Yeah [incorrect answer feedback message appears]</p> <p>Doh. Maybe it's that one well there's no like. What one d'you think that one?</p> <p>yeah</p>	<p>answer in incorrect, or which might be the correct answer.</p>
<p>[correct message feedback appears]</p> <p>Yey!"</p>	<p>"wait a sec. I think it's that one <indicating A></p> <p>Yeah</p> <p>yeah <incorrect message></p> <p>Doh. Maybe it's er that one <indicating C></p>
<p>Students can form simple conclusions supported by evidence.</p> <p>Transcripts of students carrying out multiple choice questions.</p>	<p>All the transcripts show some degree of 'test clicking to discover the answer to the multiple choice questions.</p> <p>well there's no like. What one d'you think that one? <indicating C></p> <p>yeah <correct message></p>

	<p>Yey!"</p> <p>"Yeah, yeah click on the button there, then if it's wrong I'll blame you.</p> <p><incorrect feedback></p> <p>OK incorrect"</p> <p>"... I think it's that one</p> <p><indicating B></p> <p>yeah</p> <p><incorrect message></p> <p>Doh!</p> <p>maybe it's the bottom one</p> <p><submits C incorrect message></p> <p>Nope (laughs) we're not very good at this"</p> <p><submits A correct message></p> <p>DF and EF also 'test click' to discover the answer on screen 13.</p>
--	--

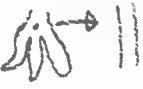
Appendix 9 IF's experiment plan, Question 6



If the hypothesis is correct, and the nucleus does control the development of the cell then you should find that whichever part of the cell the nucleus is in (the rhizoid, stem or tip) will develop fully into the acetabularia.

For further information to support the hypothesis you could repeat the experiment with a different species, *Acetabularia crenulata*.

Appendix 10 EF's experiment plan, Question 6

- ②   → cut the rhizoid + the hat off the alga.
- ③ ~~not~~ remove the nucleus from both the alga and place it into the stem of the opposite alga  
- ④ place the stem into the Petri dish. ~~not~~ to see what hat grows. 