Learning from interactions with software: a Popperian analysis

Journal Article

Learning from Interactions with Software: A Popperian Analysis

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Abstract: This paper introduces a method of analysing learning situations, based on the work of Karl Popper, and applies it to some examples of software-based teaching innovations. The basis of Popperian analysis is identification of processes of discontinuous trial-and-improvement of “strategic theories” (students’ conjectured constructions of some sort of reality) under the selection pressures provided by “concerns” (problems of special interest to the student). It requires us to examine the mechanisms by which teachers’ target problems become students’ concerns; the mechanisms by which students improve upon their existing strategic theories in the direction of target theories; and the encouragement given to the raising of new problems. The examples considered include a CD-ROM on natural selection, a CD-ROM on the work of Homer, a tool for supporting the learning of formal reasoning, a negotiation simulation, and SimCity.

Keywords: cognition; software; Popperian analysis; epistemology; psychology; problem-solving; evaluation; strategic theories; concerns; learning mechanisms

Biographical notes: James Aczel researches educational technologies at the UK Open University. He has taught on the OU’s MA in *Online and Distance Education*, and on its MSc in *Research Methods for Educational Technology*. He is also Director of the OU’s Knowledge Network, which promotes knowledge exchange about teaching and learning.

1 Introduction

There is a danger of a bifurcation in the world of educational ICT, between evaluations and research studies. Evaluations tend to employ a pragmatic, eclectic mix of methods to examine the practical effectiveness of new technologies for learning and teaching in particular subject areas. Research studies, meanwhile, draw on a plethora of theoretical traditions to examine a wider variety of research questions. Evaluations tend to be atheoretical and focus on effectiveness in particular cases; research studies incline towards generality and theoretical understanding.

This bifurcation is not necessarily seen as problematic: Typically, the audience for evaluations wants to know, bluntly, if the technology works, and is not greatly concerned about what might be seen as esoteric concepts of questionable practical relevance; the audience for research studies, on the other hand, typically wants to know about how the empirical situations illuminate theoretical notions and their domain of application rather than about a catalogue of functional details.

However, the risk with such a bifurcation is that evaluations may be so focused on the context – the students' prior knowledge, the learning activities, the design of the particular technology, the topic-specific aims of the educators, the way the technology is used with students, and the detailed learning outcomes – that one may end up being able to say lots of things about practical effectiveness in the particular case except *why* it might be effective in principle. Vary the technological or educational context slightly, and the evaluation might not be able to predict how things will be different without further extensive empirical work.

This paper introduces a theoretically-based method of analysing learning situations that, it will be argued, can enable us to devise and evaluate suggested enhancements to educational ICT.

The paper begins by outlining the theoretical beginnings of the method, which has Popper's problem-solving schema at its core. This schema is then illustrated using the Galapagos CD-ROM, software that introduces Darwin's work on natural selection. Elaborations of the Popperian psychological perspective follow, introducing the ideas of "strategic theories", "concerns" and "pedagogical learning mechanisms". These ideas are illustrated using the Galapagos software and four further packages. The analysis is then used to structure discussions about potential enhancements to the software, and to illustrate how evaluations might in principle be extended to provide more robust evidence about the reasons underpinning the effectiveness of software.

2 Popperian Epistemology

The framework introduced here is based on a psychological extension of the work of Karl Popper.

Popper is probably best known for his 1945 political book *The Open Society and Its Enemies*, and his 1972 book *Objective Knowledge*, but his work on the epistemology of science goes back to the early 1930s. Years before the Kuhnian movement, Popper persuaded many that science develops by the overturning of established ideas rather than by some gradual accretion of unchallengeable facts; that it is impossible to obtain knowledge that is certain; and that we should be critical of sources of authority because they are theory-laden and fallible (Popper, 1934).

Popper argued that knowledge is conjectural (Popper, 1963), and that it grows through criticism and testing rather than through justification and induction. He was also an early philosophical advocate of the idea that "knowledge" in the public sense comes about through complex intersubjective processes, which we would now recognise more obviously through Vygotsky. However, Popper emphasises the role of empirical testing of hypotheses in scientific discovery, rather than of subjective processes or of ideologies.

Moreover, Popper is neither a relativist nor a sceptic. He provides a plausible account of the pursuit of knowledge that exploits two ideas that have fallen out of favour in these post-modern times. The first is realism – the idea that there is a shared reality, but which is perceived in different ways; the second is the correspondence theory of truth—the idea that a statement is true if, and only if, it corresponds to reality. What has to be done in analysing the validity of claims, he argues, is to *test* claims rather than seek their sources.

Although we can never know if we have found the truth, there is the potential to discover error.

For a good introduction to the application of Popper's epistemology to educational research, see Swann (2003). Meanwhile, Bailey (2000) considers a number of applications of Popperian ideas to educational practice. We focus here on psychological aspects of how students come to know.

2.1 A Popperian Psychological Perspective

The commonsense theory of commonsense knowledge is called by Popper the "bucket theory of the mind": we open our eyes, prick up our ears, and information streams into the mind, accumulating and then being digested as knowledge. He argues that this theory is completely mistaken, and yet exerts a powerful influence on some theories of teaching, particularly the behaviourist notion of conditioning. Knowledge is treated as consisting of "thing-like" elements (ideas, impressions, sense data) *in* us, which we passively receive (unless we actively create error by interfering with or "going beyond" these given elements); higher level knowledge establishes itself by the repetitive association of these elements.

Opposed to this, "As children we learn to decode the chaotic messages which meet us from our environment. We learn to sift them, to ignore the majority of them, and to single out those which are of biological importance for us either at once, or in a future for which we are being prepared by a process of maturation." (Popper, 1972, p. 63). This learning "consists of the modification (possibly the rejection) of some form of knowledge, or disposition, which was there previously; and in the last instance, of inborn dispositions." (*ibid.*, p. 71). Moreover, this modification does not occur by passive, steady, repetitive accumulation of information, but it "always proceeds by the method of trial and error" (*ibid.*, p. 242). That is, we somehow *jump* to a theory and then test it in the hope of getting nearer to the truth.

This picture, of individuals engaged in active processes of decoding and sifting, is familiar from the Piagetian tradition that emphasises the role of consciousness rather than natural development. However, Popper emphasises, arguably more vigorously than Piaget, that individuals modify their existing theories *only* by creative, conjectural, discontinuous trial-and-error-elimination.

> "We do not discover new facts or new effects by copying them, or by inferring them inductively from observation, or by any other method of instruction by the environment" (Popper, 1994, p. 9)

Moreover, Popper asserts that *all* learning is a kind of problem-solving, in which attempts to resolve mismatches between expectations and evidence are crucial.

In order to fully understand Popper's view of psychology, one has to appreciate his distinction between three worlds (Popper, 1972). World 1 is the physical world, of stick and stones, elephants and bones. World 2 is the subjective world of our conscious experiences, thoughts and desires, hopes and fears. World 3 is the world of knowledge in the public sense: "theories published in journals and books and stored in libraries; discussions of such theories; difficulties or problems pointed out in connection with such theories; and so on." (p. 73). World 3 arises from World 2 but has an autonomous existence, in that it can be criticised and developed by anyone who has access to it. Unlike Plato's world of forms, World 3 is a product of intersubjective human endeavour, and so changes over time. World 3 includes arithmetic, gravity, astrology, the Iliad, Beethoven's Fifth, democracy, totalitarianism, and social class. It contains false theories as well as true, contested theories as well as accepted theories, problems, and arguments.

Popper argued strongly that what someone learns is heavily dependent on prior theories "of persons, places, things, linguistic usages, social conventions, and so on". For our purposes, we can see these World 3 theories as including not just the accepted canon of past thinkers' work but also the individual community's locally produced knowledge. This provides a second link to Vygotsky, and one that will be explored later in the paper.

Psychological processes, then, are analysed in terms of World 3 objects.

> "I suggest that one day we will have to revolutionize psychology by looking at the human mind as an organ for interacting with the objects of World 3; for understanding them, contributing to them, participating in them; and for bringing them to bear on World 1." (Popper, 1972, p. 156)

"Understanding a theory", in Popper's view, is understanding the problems it intends to solve and understanding why other solutions fail ("All life is problem solving"). He provides a simplified problem-solving schema to illustrate this:

$$P_1 \rightarrow TT \rightarrow EE \rightarrow P_2$$

Figure 1: Popper's basic problem-solving schema

P_1 is a shared problem-situation from which we start, and which incorporates background theories. TT is a tentative theory, an imaginative conjectural solution to the problem. EE is error-elimination, involving critical discussion or experimental tests; and P_2 is the resulting problem-situation.

Note that the most basic schema has been represented here, in order to introduce the key relationships, but the schemas become a lot more elaborate than this. For example, it would be a good idea to propose as many theories as we can to solve a given problem, then each of these tentative solutions should be critically examined in a variety of ways. Each of these attempts at error-elimination may give rise to several new and interesting problems:

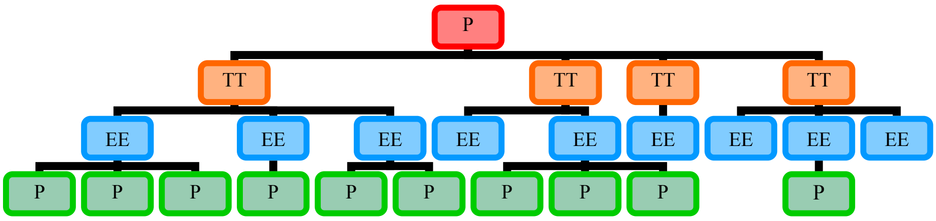


Figure 2: A more elaborate problem-solving schema

Popper introduced such schemas to illustrate arguments relating to World 3, and he himself did not explore these processes much further in psychological terms. Others have, however, taken this agenda forward.

Before we explore elaborations of the psychological perspective, an illustration of the simplified problem-solving schema might be helpful.

2.2 Illustration of Popper's problem-solving schema: Galapagos CD-ROM

The Galapagos CD-ROM was used in The Open University's *Science Foundation Course* (course code S103), to introduce some basic ideas in evolution by natural selection, although not to teach the theory directly. The main aim is to introduce students to some of the observation and note-taking skills often used in fieldwork, relating these skills to Darwin's work in the Galapagos Islands in the 19th century.

Figure 3: Screenshot from the Galapagos CD-ROM

The analysis here makes use of the accounts of the software in Taylor, Oliver, & Hatzipanagos (1995), Taylor, Sumner & Law (1997), Whitelock (1998), and Freake & Lawless (2001). Clearly there is much more known about the software (its aims and functionality, how it is used with students, and the outcomes of evaluations) than can be represented in the space available here. Inevitably the descriptions of the software, its educational context, and its evaluations are going to be rather terse. However, the purpose of this paper is to illustrate, roughly, how a particular analytical method can be applied, not to provide a complete account of the software.

What does the software enable students to do?

- Experience something of the Galapagos Islands (photographs, video, text, etc.), in relation to Darwin's observations there.
- Carry out scientific fieldwork tasks in a structured way:

  Make choices about where to observe (pan & zoom)

  Identify and categorise finches using a field guide.

  Make systematic notes.

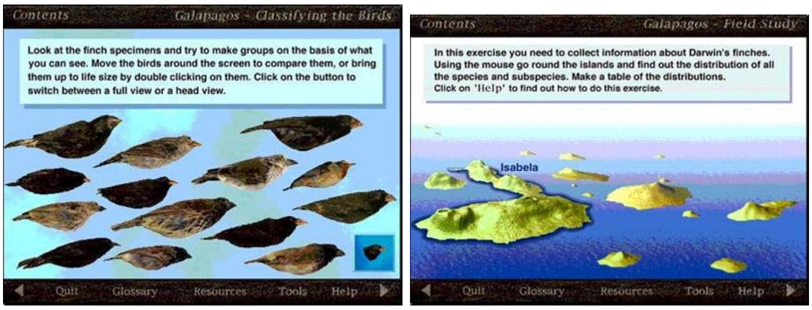


Figure 4: Some activities in the Galapagos CD-ROM

This virtual fieldtrip has a number of advantages: it is more involving than text or a museum exhibit (one student described how the videos seemed to "bring the subject to life"); it is less expensive and time-consuming than travelling to the islands; it removes the risk of not observing a range of species; it allows observation of the conditions that pertained at a previous point in time (e.g. Darwin's expedition); and it focuses students' attention on the variables that are important for this particular course. It has the disadvantage that students do not obtain experience of the messiness, practical techniques, or fortuitous opportunities of physical fieldwork.

Preliminary Popperian Analysis

A number of problems could be identified here, based on the learning objectives associated with the use of the CD-ROM in the course. We could also choose to focus on the pedagogical problem of the advantages and disadvantages of this CD-ROM over fieldtrips or museum visits; or on the curriculum problem of what observation and note-taking skills are valuable on fieldtrips looking at biological adaptation; or on other problems.

In this paper, we will focus just on the problem of whether one species of finch arrive on the islands or multiple species, although you could equally analyse the other problems:

P: Did one species of finch arrive on the islands or multiple species?

The theory (TT) under consideration, then, is that one species of finch originally arrived on the island, and that evolution alone accounts for the diversity of species observed by Darwin and the S103 students.

The error-elimination (EE) to which this theory is subjected in the course does not pretend to be in any way comprehensive (this course is at first-year undergraduate level, and endeavours to serve as a general introduction to studying science at university): it involves collecting information about the finch species, habitat and feeding habits; classifying finches into species; recording information on a spreadsheet; identifying total numbers of species and subspecies; and counting up how many are endemic to each island group. But this limited activity overtly brings in new problems (P_2) of how species are adapted to the environment; how changing conditions can lead to adaptation; the limitations of this kind of observational approach; and concepts such as ecosystems, food chains and energy transfer levels.

So far, then, the Popperian analysis of the Galapagos CD-ROM has solely consisted of identifying a basic problem-situation, and candidates for the components (P, TT, EE, P_2) of the problem-solving schema. This has not told us much. The next step is to hypothesise how students might progress through this schema: how they might grasp the problem (P) and the theory (TT), how they might learn the specifics of putting theories to the test (EE), and how they might learn from this error-elimination by formulating new problems (P_2). To take this next step, a number of ideas need to be introduced, learning the idea of "pedagogical learning mechanisms". So we return to the analysis of the Galapagos CD-ROM later in the paper.

3 Strategic Theories and Concerns

What follows are elaborations of the Popperian psychological perspective, and although the adjective "Popperian" remains, the terminology and development of the ideas are not to be found explicitly in Popper's work. The terminology has been introduced to simplify the presentation of the ideas.

Donald T. Campbell offers a sketch of a process called "Blind-Variation-and-Selective-Retention" (BVSR) which is modelled on evolution by natural selection, and which can be seen as an extension of Popperian ideas to creative thought (Campbell, 1960).

By analogy with evolution by natural selection, BVSR requires:

(i) a mechanism for introducing variation (the variations being thought trials);
(ii) a consistent selection pressure;
(iii) a mechanism for preserving and reproducing the selected variations.

The connection between BVSR and Popper's view of learning can be made explicit:

Firstly, in line with Popperian psychology, the "variations" of BVSR can be identified with World 2 theories. In order to distinguish (when necessary) between World 3 theories and World 2 theories, the term "strategic theory" has been introduced (Aczel, 1998) to refer to World 2 theories. This is appropriate, because the word "theory" in a World 2 sense is intended to label a student's conjectured constructions, expectations, dispositions, or assumptions (articulated or not), of some sort of reality in a particular context; and there is a "strategic" nature to these theories in that they solve problems. Conversely, a strategy can be considered as theoretical, in a sense, in that it incorporates expectations about some state of affairs. Note that a student's strategic theory is a personal construction (rather than a direct record of reality), but one which is potentially at odds with what is there. Following William James, one could see these products of the human mind in instrumental terms, as adaptations to reality. Therefore, in contrast with some phenomenographers, this perspective allows some strategic theories to be seen as "better" than other strategic theories.

Secondly, the "selection process" of BVSR can be characterised (following the Popperian model of understanding outlined above) as a World 2 problem of special interest to the individual. Because the word "problem" is being used in a technical sense, the term "concern" has been introduced as a label (Aczel, 1998). Concerns would include desires, motivations and fears; in short, anything that exerts a psychological selection pressure on the formation of theories. A concern is a World 2 construction like a strategic theory, is usually unstated, and is what we as researchers might conjecture is engaging students' minds during a period of time. They incorporate what cognitive scientists might call the "student's problem-situation model".

So, with respect to World 2, we will talk about "strategic theories" and "concerns", and learning is portrayed in terms of processes of discontinuous trial-and-improvement of strategic theories under the selection pressures provided by concerns.

3.1 Comparison with other approaches

It might be helpful, before moving on to consider examples of these processes, to consider how these ideas relate to other approaches to thinking about learning.

Campbell argues that BVSR is "fundamental to… all genuine increases in knowledge, to all increases in fit of system to environment." (Campbell, 1960, p. 380). Even mechanisms that shortcut BVSR have themselves been originally achieved by BVSR. Campbell also argues that such shortcut mechanisms still involve BVSR at some level, although this will not be assumed here.

Campbell notes that the BVSR model of thought…

> "… joins the Gestaltists in protest against the picture of the learning organism as a passive induction machine accumulating contingencies. Instead, an active generation and checking of thought-trials… is envisaged. … Poincaré's (1913) aesthetic criteria and the Gestalt qualities of wholeness, symmetry, organised structure, and the like can be regarded as built-in selective criteria completely compatible with the model." (p. 389)

However, unlike the Gestaltists, strategic theories do not spring fully formed into being:

> "While 'insight' is accepted as a phenomenal counterpart of the successful completion of a perhaps unconscious blind-variation cycle, its status as an explanatory concept is rejected, especially as it connotes 'direct' ways of knowing." (p. 390)

Campbell decries the deification of "the creative genius to whom we impute a capacity for direct insight instead of mental flounderings and blind-alley entrances of the kind we are aware typify our own thought processes" (p. 391). However, he also lists four ways in which thinkers may be expected to differ, according to the BVSR model:

1. The accuracy of representations of World 1.
2. The number and range of variations in thought trials produced.
3. The accuracy and number of selective criteria.
4. The ability to retain solutions.

Of course there are difficulties with the model: Firstly, Campbell himself notes a number of reasons why it is difficult to test. Secondly, the exact nature of the "mechanism for introducing variation" and the "mechanism for preserving and reproducing the selected variations" are left as mysterious (although it does not affect the analysis). Thirdly, it is not clear to what extent the "shortcut mechanisms" Campbell describes might be more influential in practice than simple BVSR.

Nevertheless, we can speculate that variation could be introduced by something like analogical reasoning (Rumelhart & Norman, 1981), which would enable students to identify similarities of problem structure; and that memory processes play a crucial role in preserving and reproducing strategic theories between problems.

It is worth drawing attention to some of the characteristics of strategic theories, to help delineate the similarities and dissimilarities with, for example, Bartlett's schemata

(Bartlett, 1958), the cognitive structures of Piaget or Bruner, Schank's scripts (e.g. Schank, 1982), the productions of ACT* (Anderson, 1983), or Sweller's schema (e.g. Sweller et al., 1983).

A strategic theory is *implicit* and *unarticulated* because the knower is perhaps rarely aware of more than a small part of it at any one time and it cannot be transferred directly from one person to another. It is also *imprecise* because it is not concrete or formulated in logical terms (unlike the typical mental model of Johnson-Laird, 1983); and although it was constructed in response to a particular concern, and is therefore *contextual*, the vagueness of its construction might help transfer between concerns. There are *assumptions* built into strategic theories, and we can discover new things in them that we did not realize by means of *reflection*. Although strategic theories can quickly fade if they do not play a role in everyday living, they can *linger*. They can involve *action*, or they might only involve *thought*.

It is likely for there to be *commonalities* between different people's strategic theories because they have tackled similar problems in the past. In particular, it might be reasonable to suggest (following Kant) that human physiological development has a very strong early influence on the propensity to construct certain theories - for example for space, time, quantity, quality and relation - that might then act as templates or constraints on future constructions.

Language, culture and tools are clearly foremost aspects of World 3, and they may very well form part of the background theory to problem situations, or they may be the subject of theorising. However they also may have additional roles to play in the analysis. For instance, language is used to describe some shared reality, and to argue about the difference between descriptions of that reality and observations of that reality. Tools, too, have a special role to play in the analysis. They can facilitate the formulation of problems, the creation of theories and the conduct of error-elimination. Finally, as we have seen, social interaction is central: It provides the participation in shared problem situations that is so often the medium for learning, and the intersubjectivity that enables World 2 to produce World 3. But more than this, the socially-produced World 3 constitutes a reality that frames learning.

Concerns, meanwhile, include anxieties about social and technological interactions, and about personal failure. They include attitudes, dispositions, desires and motivations. There is no reason to suppose their character is very different to that of strategic theories, as outlined above, except that emotion and purpose play a much strong role.

We return now to consider the processes by which World 2 strategic theories are constructed as a consequence of concerns.

4 The notion of pedagogical learning mechanisms

To illustrate how these processes work, the simplified problem-solving schema can be converted into pedagogical terms…

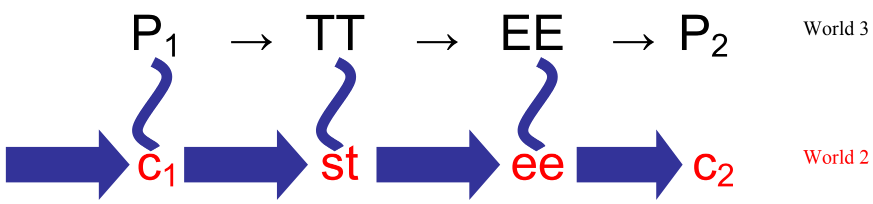


Figure 5: Pedagogical extension of the basic problem-solving schema

A student has a concern (c_1), conjectures a strategic theory (*st*) to address the concern, subjects it to some sort of error-elimination (*ee*), and the concern is altered, not least simply by virtue of having engaged in the investigation of the original concern.

Now in educational endeavours, there are very often particular problems with which teachers intend their students to engage ("target problems"). So we might consider how students grasp such problems and make them their own. There are also typically ideas, frameworks, themes, and the like with which students are expected to gain familiarity ("target theories"). So we might consider how students grasp these theories.

The term "pedagogical learning mechanisms", then, refers to the "how" of the grasping: the means by which teachers' target problems become students' concerns; the means by which students improve upon their existing strategic theories in the direction of target theories; the means by which students come to appreciate appropriate error-elimination in the subject domain; and the encouragement given to the raising of new problems.

The essence of Popperian analysis of learning scenarios is to ask questions such as:

→ P What are the target problems (P_1), if any, with which teachers intend their students to engage? By what means can the target problems become concerns? ($\rightarrow c_1$ and $P_1 \sim c_1$) Successful mechanisms here would take account (deliberately or not) of students' existing concerns (including what might motivate them) and background knowledge.

→ TT What are the target theories (*TT*), if any, which teachers intend their students to grasp? By what means can students grasp target theories? ($c_1 \rightarrow st$ and $TT \sim st$) Successful mechanisms here would take account (deliberately or not) of students' typical theories and difficulties in relation to the problem situation.

→ EE How are students supported in appreciating how theories are put to the test (EE) in this subject domain? This entails taking account of shared knowledge practices. Successful mechanisms here would encourage autonomous EE, and provide feedback to help students improve on their theories.

→ P' And how are students encouraged to pose new problems?

4.1 Comparison with other approaches

Figure 5 suggests two types of learning mechanisms. For example, looking at the question of how target problems can become concerns, there are two routes: $\rightarrow c_1$ and $P_1 \sim c_1$ (horizontal and vertical processes). The first entails explicitly starting with students' existing concerns and knowledge, and encouraging students towards something like P_1; the second type of mechanism involves a more direct approach resembling "telling".

Similarly, in relation to the question of how students can grasp target theories, there again appear to be two types of mechanism suggested by Figure 5: $c_1 \rightarrow st$ and $TT \sim st$. The first entails paying attention to students' typical struggles with the particular problem situation, and finding ways to encourage students to improve upon their existing strategic theories in the direction of target theories, to address the problem c_1; the second type of mechanism focuses on explaining the target theory *TT* but not necessarily relating it to the problem P_1.

This paper will not be exploring this possible distinction much further, however it is important to point out that although it might be possible to see parallels here with the alleged dichotomies between student-centred, discovery learning on the one hand versus teacher-centred, "chalk-and-talk" teaching on the other, it is the Popperian case that even in the latter situation, students *are* learning by active construction. At no time are students simply "absorbing" knowledge.

As Popper (1972) puts it:

> "We learn about our environment not through being instructed by it, but through being challenged by it." (p. 266)

Another way (not overtly Popperian) of looking at Figure 5 is to see the World 3 processes as a much-simplified model of the epistemology of a *social practice*, and the World 2 processes as how the apprentice participates in that practice's epistemology. The vertical processes then constitute initiation or enculturation into the practice's epistemology. Again, this perspective is not explored much further here.

It is possible to relate learning mechanisms to the "layered analytical framework" of Taylor et al (1997) for describing educational software. Their first level ("educational aims") corresponds to target World 3 objects (*TT*, P_1, *EE*) as defined by the syllabus and the needs of the student population. Taylor et al's second and third levels ("teaching strategies" and "task semantics") have similarities with learning mechanisms, in that the teacher's pedagogical approach, the range of student activity and the support provided by learning resources (such as books or educational software) largely comprise the means by which World 3 objects are grasped.

Taylor et al consider three categories for analyzing such support: (1) techniques for promoting reflection, (2) structuring devices helping learners through tasks, and (3) methods for keeping learners motivated. Popperian analysis would not refer to "reflection" as such, but the World 2 horizontal arrows in Figure 5 suggest where creative student thought would take place ($c_1 \rightarrow st$, st $\rightarrow ee$, $ee \rightarrow c_2$). "Motivation", meanwhile, is an important aspect of developing concerns ($\rightarrow c_1$) and can draw on mechanisms such as authenticity, relevance, fun, pacing, and achievement.

In simple terms, then, Popperian analysis invites us to consider the following questions:

→ P What are the mechanisms by which target problems become concerns?

→ T What are the mechanisms by which students improve upon their existing strategic theories in the direction of target theories?

→ EE How are students supported in comprehending error-elimination appropriate to the subject domain?

→ P' How are students encouraged to pose new problems?

We now consider these questions in relation to the Galapagos CD-ROM and other software.

5 Illustration of learning mechanisms

5.1 Galapagos CD-ROM

→ P The software attempts to make the problem of Darwin's finches into students' concerns by means of introductory videos that provide an historical context to Darwin's work, and readings from Darwin's journal; by stunning photos; by highlighting Darwin's mistakes; and by alternating watching and reading with practical activities.

A potential weakness of these →P mechanisms is that the software allows the student little leeway in formulating the problem: the student cannot start with the problem of how different species of finches could evolve, for example, or choose to study turtles instead of finches. However, one can understand the designers' decision to restrict problem formulation in this way, to minimise the complexity for students new to degree-level study.

→ T The software encourages students to develop a theory about the finches by means of a strong narrative line; by asking questions to encourage students to pay attention to the narrative; by episodic structured tasks that lead towards desired conclusions; by giving students a small element of control over what they can learn about and in what order; and by enabling students to construct their own classifications of birds. Arguably the strongest encouragement comes from multiple choice questions that require students to make inferences: i.e. to use their theories to make testable predictions. For example, students are asked to predict the effects of specific climatic changes on finches' beak size and their population size. It might be argued that students would be more likely to both understand and remember theories derived by themselves than directly explained by others.

In terms of potential weaknesses in these →T mechanisms, the software countenances only a limited range of theories, presumably in order to guide students towards the target theories. The evaluations, it should be noted, do not set out to provide insight into how the software might take into account students' prior theories or their typical difficulties with target theories.

→ EE The students are given structured tasks to do. They are asked to compare their own classifications of birds with those of 19th and 20th century researchers; and are also asked to consider why 19th and 20th bird classifications are different, encouraging them to consider how methods of testing theories change.

A potential weakness of these →EE mechanisms is, as with →P and →T, their constrained nature. In addition, while one of the formative evaluations revealed students' difficulties in handling data in an external program (a finding that led the necessary data analysis functionality to be incorporated within the Galapagos software itself), there are no substantial findings relating to whether students wanted to try alternative ways of testing theories, or whether they found it difficult to interpret the results of the tasks.

→ P' There are more materials included in the software than required for the tasks, allowing the possibility of motivated students exploring further.

There is no evidence in the evaluations, however, that this was sufficient motivation. On the contrary, many students reported spending longer on the assigned tasks than they had expected.

It is difficult to see value in the Popperian analysis method from a single case study, so we now identify the learning mechanisms in further software packages, before considering advantages of the method.

5.2 Jape

The second illustration of learning mechanisms comes from a program called "Jape", which is used by Computer Science undergraduates to learn formal logic. The analysis here is based on Aczel et al (2003).

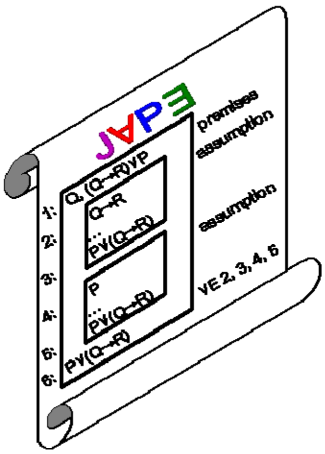


Figure 6: The software Jape is a kind of "proof calculator"

What does the software enable students to do?

Jape enables students to see the effects of applying a rule to a line of a natural deduction proof.

The software presents a conjecture to students. For example:

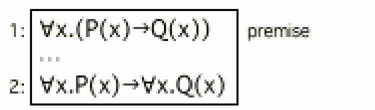


Figure 7: Example of a conjecture in Jape

The students then select, from a menu, a rule to apply to a part of the proof.

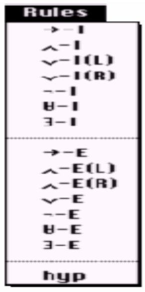
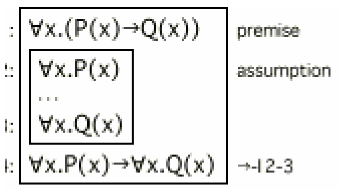
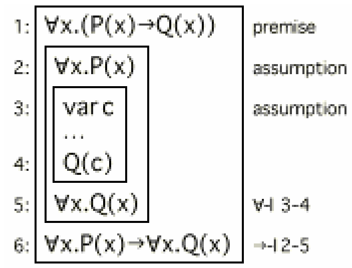


Figure 8: Rules menu in Jape

So, in this instance, when the optimal rule in this situation is applied, the screen shows the students the consequence:



and then…



And so on…

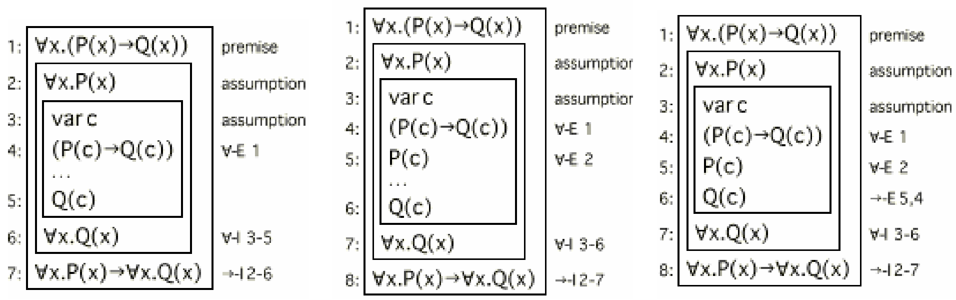


Figure 9: Proving in Jape

A big advantage of Jape is that students can consider many more examples than would be possible on paper, because there is no writing or drawing to do; another big advantage is that the software calculates the effect of rules accurately.

Popperian Analysis

The main problem is:

P: How can proofs be constructed for conjectures in first order propositional and predicate logics?

→ **P** The software presents an implicit challenge to see how many proofs can be completed. The evaluation also established that because students typically use Jape after practice on paper, they are often so relieved at no longer having to draw out proofs laboriously that they start to enjoy the challenge. However, in truth, the strongest motivation here is likely to be the exam…

→ T Theory creation is encouraged by ease of testing (see →EE) and by careful sequencing of conjectures. The software also prevents users from making illegal moves (whereas on paper, illegal moves are often done accidentally) and inhibits them from making certain unhelpful moves.

The evaluation provides details of students' difficulties in grasping the target problems and theories. In particular, it is clear that while the software helps those students who start with certain basic strategic theories to improve upon these (their proving skills progress noticeably), those students who start without these rudimentary strategic theories tend to resort to a kind of *brute* trial-and-error approach of selecting rules more or less at random. This approach is unable to help them move to the target strategic theories (proving skills do not progress).

→ EE Students are able to test their theories about the best rule to apply in a situation, because Jape provides instant feedback on the effects of the rule, and provides subtle visual cues that a proof is heading in the right direction. The software also frees the student from drawing, and this allows experimentation.

A clear weakness of the error-elimination mechanisms is that because the software always takes on the task of applying the logic rules, the students then find it difficult to fend for themselves on paper. Another weakness is that sometimes the feedback does not help the students debug their strategic theories. Nevertheless, the evaluation clearly showed that Jape very often allows students to discover flaws in their fixated reasoning.

→ P' Students are able to enter their own conjectures. There is evidence from the evaluation that only a tiny proportion of students did so.

5.3 Homer CD-ROM

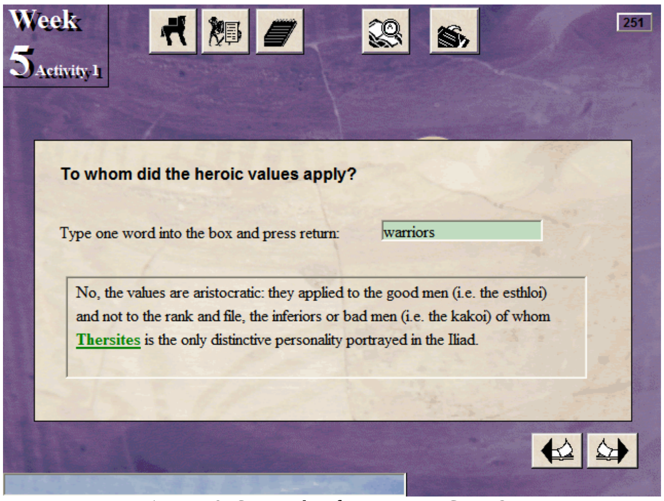


Figure 10: Screenshot from Homer CD-ROM

The third example is a multimedia resource about the poems of Homer and their social context, and it is used in the second-level course *Homer: Poetry and Society* (course code A295). This analysis is based on Chambers & Rae (1999).

What does the software enable students to do?

- Access in one place texts, activities, photos, maps, audio, video and other resources, relating to the Homeric poems and to archaeological sites of Ancient Greece. It contains around 700 000 words of text, about 300 images, 22 video clips and 70 minutes of audio.
- Search, bookmark, and make notes; enables easier engagement with texts.
- Test their own understanding via interactive questions

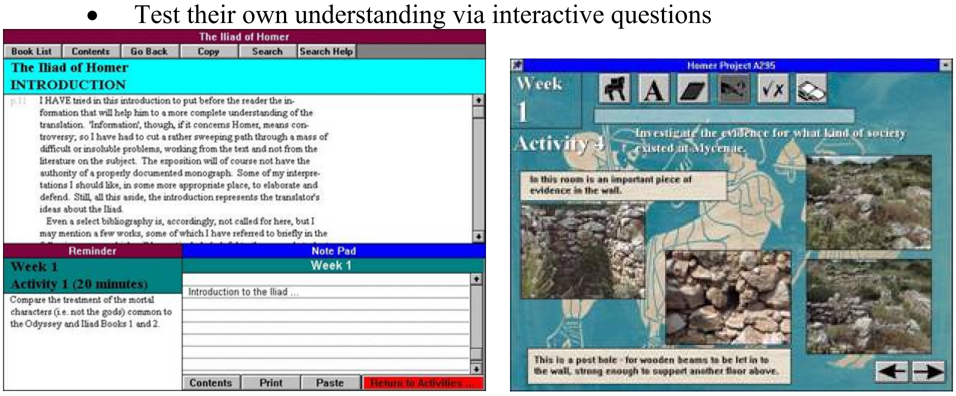


Figure 11: More screenshots from the Homer CD-ROM

Popperian Analysis

P: What are the relationships between poetry and society at the time of Homer?

Note that we do not have information on students' particular difficulties with this subject matter, nor on how the text or activities have been constructed to address these aspects of learning. So we can but conjecture the learning mechanisms.

→ **P** The software aims to motivate this problem by means of the richness of the multimedia resources and prompts provided by the interactive questions.

As with the Galapagos and Jape software, the problems of the Homer software are chosen by the course designer not the student. As with the Galapagos software, the evaluation does not set out to provide evidence as to how the software might be motivating target problems by challenging students' prior theories.

→ **T** Students are encouraged to construct strategic theories by means of interactive questions. Some questions ask for one-word answers; some are multiple-choice; some entail students making notes; and some involve comparisons, particularly between passages of text. Encouragement to construct theories is also supported by the convenient way in which a range of resources that would otherwise be difficult to compare are gathered together and made accessible through searching.

As with the Galapagos software, the evaluations do not set out to provide insight into students' typical conceptual difficulties.

→ **EE** The interactive questions encourage students to use a range of resources to check theories. For example, the multiple choice questions force students to consider how to weed out wrong answers; the multimedia resources then enable these error-elimination steps to be carried out; and finally the software shows an expert's response to the question, and hints as to what counts as relevant evidence in the academic community.

As with the Galapagos software, the evaluations do not set out to examine the success of feedback provided by the software in moving students towards target theories. However, a difference between the Homer and Galapagos packages is that the Homer software makes the multimedia resources available from the start, which opens up more possibilities for error-elimination; while the Galapagos software constrains the range of resources at each question, which focuses student attention on the principal error-elimination steps.

→ **P'** It is hoped that students are suitably inspired by the examples to consider their own questions.

5.4 SimCity

Figure 12: A SimCity movie

The simulation game SimCity allows the user to build and run a city, and it manages to highlight the excitement and importance of what might otherwise be seen as dull issues of business zoning, transport policies, budgets for leisure facilities, and so on.

As described in Chambers & Rae (2000), SimCity has been used in a limited way in the third level course *Cities and Technology* (course code AT308) in that students watch, in movie mode, examples of how housing, employment and transport infrastructure can interact.

Popperian Analysis

P: How are the physical forms of cities influenced by technology?

It does not take sophisticated pedagogical analysis to calculate that students are likely to gain more from a tailored interactive version of SimCity than from a movie version. Indeed, the software is apparently widely used on US undergraduate city planning and economics courses. Note too that the evaluation does not provide information on students' particular difficulties with this subject matter. However, Popperian analysis is used here to draw attention to specific suggestions with respect to the problem above.

→ **P** Could provide opportunities for competitive and collaborative "playing" and model designing. Rather than posing a problem in words, particular scenarios could be created to enable students to identify the problem for themselves.

→ **T** Could allow students to test claims by building their own cities or their own models, with different technologies becoming available (or not) at different moments in history. Sequencing from simple to complex could also help here.

→ **EE** Students could be asked to apply theoretical principles to a range of simulated situations; or to apply a range of theories to a single case; or to critique and improve upon the models underlying SimCity.

→ **P'** Once caught up in the spirit of the enquiry, students might very likely choose to explore scenarios with unusual physical or technological features.

Another well-known and well-designed simulation game, Age of Empires, provides insight into historical situations. Rather than telling how the Athenians managed to defend their city from the Spartans for so long, students can be given the same troops, technologies, and resources; and they will re-invent the Athenians' strategies for themselves. Even disease and wise old philosophers can be modelled.

These simulation games are now playable online, which opens up the possibilities for making error-elimination simultaneously more social (thus modelling the growth of knowledge more accurately) and more sophisticated (allowing for human critical and aesthetic judgments to play a role). Perhaps this provides a way forward for the Homer problem.

Lest the idea be formed that this analysis is simply leading to identifying limitations of existing software and new ways to extol the virtues of new technologies, it should be pointed out that the method also engenders criticisms of suggested enhancements. It is possible, for example, that students end up *just* playing games. The details of how activities are constrained in such a way as to make the learning mechanisms most effective need to be carefully tested out.

5.5 D833 using Lyceum

Lyceum is a Windows-based online synchronous audio-conferencing system. It includes multiple rooms, a collaborative whiteboard, voting, and collaborative document annotation.

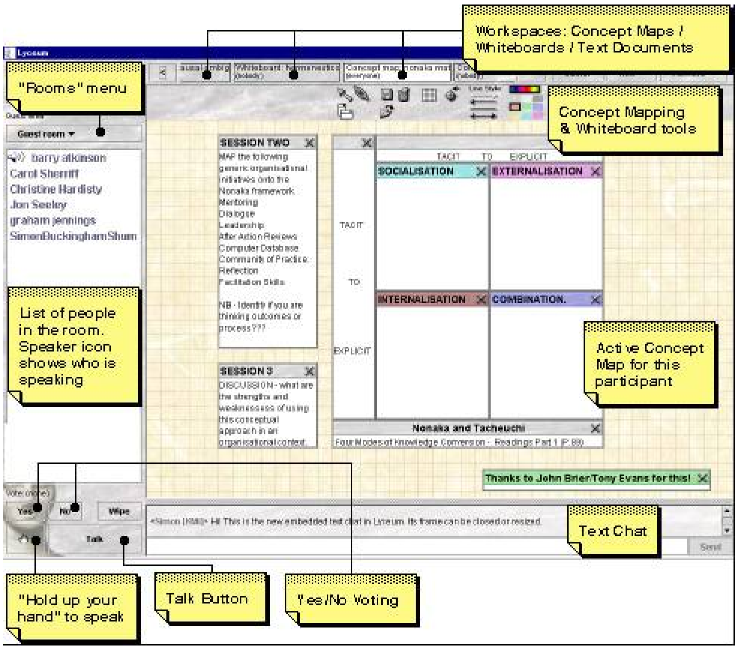


Figure 13: Lyceum facilities

Lyceum has been used in the postgraduate social science course *Environmental Practice: Negotiating Policy in a Global Society* (course code D833). This analysis is based on Thorpe (2002) and Price (2003).

What does the software enable students to do?

- Engage in a simulation of negotiations at the UN, participating in nine 2-hour negotiation sessions
  - Take part in working groups and plenaries
  - Collaborate on documents
  - Use "whisper spaces" to conduct private negotiations
  - Take part in formal votes
- Represent the interests of a country, drawing on a 'country profile' and online resources

Popperian Analysis

P: What are the processes of international negotiation of legal instruments on the environment?

→ **P** The simulation, particularly the fact that all students play a distinctive role, certainly engages attention. As Thorpe (2002) points out, though, there is a difference between playing the role of a diplomat and learning to be a scholar in the social sciences. So, for example, alliances seemed to be formed on the basis of personalities rather than geopolitics (Price, 2003). It is therefore an important role for the teaching materials and the tutor to encourage students to refine the scope of problems in an appropriate academic manner. There is little evidence available, though, about how successful this was.

→ T Students are able to experiment with and examine the processes of negotiation in the light of theory. The evaluations suggested that students found the simulation very useful in enhancing their understanding of the target theories (Price, 2003). In principle, the simulation and subsequent discussion provide opportunities for a range of theories to be generated. There is little evidence available, though, about whether this was the case, or about the extent to which the simulation takes students' typical theories and difficulties into account.

→ EE Student opinions about the course strongly indicated that the simulation "fostered a great sense of community" and helped them "think reflexively on the relationship between theory and practice" (Price, 2003). In principle, the simulation and subsequent discussion provide opportunities for a range of criticisms of theories to be generated and illustrated. However, the evaluations did not aim to test students' academic understanding of processes of error-elimination in the domain. There is a danger in such simulations that students give priority to empirical data from the simulation rather than from wider research. In this regard then, as with **→P** mechanisms, there might be a role for the materials and tutor in focusing students' attention.

→ P' It is plausible that new problems arise naturally out of the engagement, although there are no examples available at this time.

Up until now in this paper, the analysis has largely focused on the construction by individuals of World 2 knowledge, in social contexts that include World 3 knowledge. When analysing Lyceum, however, it is possible, following Vygotsky, to focus on the social construction of World 3 knowledge.

In Popperian terms, the community of participants in the simulated UN conference dealing in theories about environmental issues has analogies with the wider scientific community looking at these issues. Scientific evidence is brought to bear on contested issues; problems are raised to do with the limitations of available evidence; contradictions are noted; there is competition but also a recognition that cooperation and a commitment to compromise can benefit all; and it is even within the power of these delegates to initiate the collection of more evidence. Within the simulation, theories might be discussed that conflict with those accepted or rejected in the wider community, and yet the reality of these idiosyncratic theories cannot be denied in understanding the simulated negotiation processes because of the consequences for what is agreed in the simulated UN. These local theories are therefore taken to be part of World 3.

Despite the innovative nature of this use of audio-conferencing software, Popperian analysis has suggested some possible limitations with respect to the target problem. However, how serious these limitations are is unclear without empirical research into the extent of students' difficulties, particularly in grasping error-elimination in this subject domain.

Incidentally, the "social practice" interpretation of Figure 5, mentioned earlier, would provoke an alternative way of looking at the use of Lyceum to teach processes of international negotiation. In this interpretation, students are being initiated into a practice by approximating the actual epistemological practice rather than playing a peripheral role within it. Such an approximation would therefore be strengthened by realistic modelling of the power relations that exist between participants.

6 Using the analysis

We have now considered several examples of applying the method. The approach has been broad-brush, and ideally one should have looked at students' detailed problem situations rather than whole software packages. But why are we doing this?

First of all, it is to understand how learning is occurring. So, for example, we have seen some learning mechanisms for →P:

- providing an authentic account of the historical context (Galapagos, Homer)
- emphasising the fallibility of a researcher (Galapagos)
- prompting (Galapagos, Jape, Homer)
- providing a rich multimedia experience (Galapagos, Homer, SimCity)
- exam (Jape)
- a game-like environment (SimCity)
- pacing and a sense of achievement (Galapagos, Jape, Homer, SimCity)
- alternating watching or reading with practical activities (Galapagos, D833)
- discussion (D833)

We have also seen some difficulties with the mechanisms in these programs, in particular that, with the exception of D833, they allow little room for the student to initiate problems and to formulate them in her or his own way. In addition, the programs have varied in the degree to which they appear to take account of students' typical strategic theories and difficulties.

Furthermore, we have seen how inferential questions (Galapagos, Homer), narrative (Galapagos), sequencing (Jape, Galapagos), search (Homer), consequentiality (Jape, SimCity), simulation (Galapagos, D833, SimCity) and discussion (D833) can be learning mechanisms for →TT. Opportunities for error-elimination have been provided by software feedback on responses (Galapagos, Homer, Jape), resource banks (Homer, D833) and discussion (D833). However, the scope for error-elimination in all the programs has been constrained by the designers, both in terms of the types of error-elimination integrated into the software and in terms of the range of feedback achievable. Moreover, none of the programs provides much encouragement for problem-posing following error-elimination.

Nevertheless, there is any number of ways of characterising the success of such software. What would enable us to distinguish the fertility of different characterisations? One suggestion is that any such characterisation should help us to devise and evaluate suggested enhancements to the software.

Suppose, for instance, the question is asked of the Galapagos CD-ROM, "How would introducing peer-to-peer discussion be helpful?" One response might be that observing or engaging in discussion with others could help the problem to become a concern for students who are not already taken with it. It could encourage students to seek clarification of strategic theories they are worried about. It probably would not (it might be argued) help their comprehension of error-elimination appropriate to the subject domain, or encourage them to pose new problems.

So the method has generated some specific claims. These claims are likely to be contested by others involved in the design team; but they are specific claims about a possible innovation and so can be tested empirically.

One could also consider the potential for copying learning mechanisms between programs. For example, perhaps "alternating watching or reading and practical activities" might help students using Jape; or maybe "emphasising the fallibility of a researcher" might help students of Homer. For example, just as the stories of Darwin and later scientists provided a means to draw attention to changing methods of error-elimination in the study of species, the changing perceptions of Homer and the poetry might highlight how methods of critical engagement in the academic study of this field have changed.

In the case of the Homer CD-ROM, some successful learning mechanisms already within it could be built upon. The success of the Galapagos CD-ROM in alternating watching and reading with practical activities, and in a strong narrative line divided into episodic structured tasks might well be worth applying more fully in the Homer CD-ROM to aid creation of strategic theories. Strengthening students' ability to test such theories might prove more difficult here than in the Galapagos CD-ROM or in Jape, because the arguments are less easily reduced to quantitative or systematic representations. So finding ways to combine the CD-ROM with some form of structured discussion with experts might be helpful.

Another example arises if a member of the design team found the proposed learning mechanism →EE for the Galapagos CD-ROM to be weak. The question would then naturally arise "So how *could* we enable students to appreciate what error-elimination might mean with respect to the theory of natural selection?" The course team could brainstorm this pedagogical question, and come up with some suggestions. So, for example, it might be suggested that students could be connected to a live expert at an appropriate point, or that that students would be asked to conduct their own analysis of a situation similar to that of the finches without the structured tasks provided as support. And then these suggestions could be tested out with prospective students, using mock-ups, phenomenographic interviews or whatever. Or maybe the claim that the →EE mechanism is weak might be disputed and put to the test.

So the method is again helping to structure pedagogical debate and provide testable hypotheses. Testing the hypotheses is not trivial, of course, but not impossible either; and they are generated by educators' understanding of students' difficulties and of a range of possible teaching strategies. It is not claimed that this Popperian analysis is the only way to structure pedagogical debate.

7 Extending evaluations to provide insight into learning mechanisms

Evaluations of educational software, even if thorough, would not of course be focused on this style of analysis. Such evaluations are expected to find out about issues such as students' perceptions of the value of software as a whole, the study time spent on it, interface usability, technical difficulties, and the "fit" with other aspects of the course.

These evaluations typically make use of a variety of techniques, such as surveys, observations of students working at the computer, expert walkthroughs, interviews about students' perceptions of the software, and test scores. As we have seen with the evaluations used here, such techniques can in fact provide some evidence about the extent to which planned learning mechanisms meet with success, even if this is not the overt goal. Typically, students generally rated the software activities as interesting, enjoyable, and helpful for learning and remembering; and they particularly valued the interactivity of the learning experience and the "high production values" of the visual presentation.

What evidence is missing, then, from even thorough evaluations of this software that would augment a Popperian analysis?

One kind of evidence is of the extent to which students have accurately grasped the target problems and theories of the course. This evidence could be sought using clinical interviews and detailed script analysis, and would allow a good test of the intended learning mechanisms described above, and would also identify students' typical theories and difficulties with the topic. Another kind of evidence is of the effect of variants of contended aspects of the design on students' grasp of these problems and theories. Such evidence would not only provide insight for the designers into suggested enhancements to the teaching of the particular topic, but would allow researchers to build an evidence base in relation to learning mechanisms in general.

Beyond this, Popperian analysis would want studies to obtain evidence relating to questions such as:

- To what extent are the intellectual problems those of the student, rather than just of the course designers?
- In what ways are the target problems motivated by challenges to students' prior theories?
- How is autonomous trial-and-error-elimination encouraged?
- To what extent does feedback provided by the software help students to improve their theories?
- In what ways does the software help students to appreciate knowledge practices in the domain?
- How does the software encourage students to pose new problems?

8 Critique

Limitations of this paper

In this introduction to Popperian analysis, it has been illustrated how the method can be applied in broad terms. There are some limitations to this account, though.

Firstly, only the broad brush problem situations of the given topics have been considered, rather than the detailed problem situations that an educational software designer or researcher would need to consider. Much of the detail about the context of use that crucially affects the practical effectiveness of software has been neglected. This is acceptable here, though because the analysis is not *per se* about effectiveness in practice, but about learning mechanisms in theory.

Secondly, the focus has largely been on desktop software, and a fairly limited range of that too. This is because such technology seems to be the best analysed within the Open University in terms of subject domain knowledge (and consequently provides the level of detail needed about problems, theories and error-elimination). But the method has applicability across the field of educational technology. It should also be noted that all the software examined here has been upgraded since evaluation.

Thirdly, the studies cited contain some – but not all – of the empirical detail one would need to carry out a detailed Popperian analysis. This is not to criticise those studies; they typically and quite rightly focus on the extent to which the particular technological innovation achieved educational aims, and they do not usually have a remit to look systematically and in depth at students' difficulties and hypothesised learning mechanisms.

Finally, the style of analysis has been much simplified, focusing on aspects that are easiest to grasp. In particular the most basic problem-solving model has been used.

Nevertheless, it might be possible to have seen some value in exploring Popperian analysis as a possible means to try to understand learning situations.

Possible limitations of the method

The advantages of the method have been made clear: it is a systematic analytical technique for clarifying and testing pedagogical purposes and strategies; it highlights students' prior knowledge and motivation, and their learning journeys; it emphasises discipline knowledge; and it avoids the caricatures of transmission versus construction.

Nonetheless, some limitations of the method are starting to appear.

Firstly, it appears to work best in detailed problem situations, and so it lends itself better to assessing how variations in the design of a technology might be effective for a given problem situation than to assessing how a given technology might be effective for a variety of problem situations.

Secondly, the method does not work well with software that does not incorporate substantive curriculum problems or theories with which students are expected to engage. Email and concept-mapping software are examples.

Thirdly, it does not take account of meta-cognitive strategies (e.g. self-reflection) or preferences for learning; and it provides no special techniques for analysing language the mediating role of tools in activity, or the life of communities. This suggests it could be used in conjunction with a framework such as activity theory.

Fourthly, it can be hard to operationalise the method in strictly procedural terms – in the style of cognitive modelling – which is an issue if one wants to make and test old-fashioned claims about prerequisites, sequencing, chunking or exercises.

Finally, it is not clear to what extent strategic theories and concerns are manifestations of situated cognition that do not transfer easily between problem situations.

Yet despite these possible limitations, the value of exploring the approach is to discover how far a single vision of learning can take us:

> "The theory of knowledge which I wish to propose is a largely Darwinian theory of the growth of knowledge. From the amoeba to Einstein, the growth of knowledge is always the same: we try to solve our problems, and to obtain, by a process of elimination, something approaching adequacy in our tentative solutions." (Popper, 1972)

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