Dry Laboratories in Science Education:
Computer-based Practical Work

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Abstract

Practical (laboratory) work in science education has traditionally been used to allow students to rediscover already known concepts and ideas, to demonstrate concepts taught in the classroom or, in the case of inquiry-based science curricula, to teach concepts. Often, these laboratory practicals do not achieve their goals and may even confuse or demotivate students. It is not that using 'wet' practicals is intrinsically wrong; rather, it is that they are often used for the wrong reasons. They do have a place in science curricula -- for the conveyance of tacit knowledge that can only be achieved in the laboratory setting. In our view, their use should be restricted to that.

Non-laboratory practicals (`dry labs'), and especially multimedia practicals, tend to be used for completely different reasons. They are best used to help students achieve specific cognitive skills (such as analysis, synthesis and evaluation) needed to practice science and to carry out scientific inquiry. This article sketches the problems associated with the use of dry laboratories in science education, presents design considerations for the use of such practicals in science education and presents examples of innovative non-traditional practicals.

Traditional Wet laboratories

> Laboratory work is an accepted part of science instruction. Given its important place in the education of youth, it is surprising that we know so little about its functioning and effects (Gallagher, 1987: 351)

Although most scientists and science teachers look back on their experience of university practicals positively, and feel that the `average' practical they followed was of reasonable quality and was worthwhile, there are some major concerns. A review of the literature (Kirschner & Meester, 1988) dealing primarily with undergraduate science education yields the following criticisms from students and teaching staff.

Practical work provides a poor `return of knowledge' considering the amount of time and effort invested by staff and students.

- All too often, work done in a laboratory simply verifies something already known to the student.
- Too much time is wasted having students perform trivial experiments.
- Usually, the practicals cannot fail. Years of effort have produced foolproof `experiments', where the right answer is certain to emerge for everyone in the class if the laboratory instructions are followed.
- It is not at all uncommon to find that students have no understanding of the processes and techniques which they have previously used in the laboratory.
- Non-trivial experiments tend to overwhelm students. Either they require the student to solve problems beyond their comprehension or they allow insufficient time for satisfactory completion.
- Students almost never have the chance to spend time watching an expert conduct an experiment.
- The supervision of laboratory work is often inadequate, in that assessed work is often not marked and returned soon enough to have an effect on learning. Assessment (and penalising) is often arbitrary and has little teaching value; constructive feedback is often lacking.
- Practicals are often seen as isolated exercises, bearing little or no relationship to earlier or future work.

Faulty Motives for Using Laboratories

The most common motives for employing practicals in a Natural Sciences curriculum relate to the substantive structure of science: illustrating theory, achieving meaningful learning, gaining theoretical insight into natural phenomena. In all three arguments, the value of the practical is seen to lie in its subservience to scientific theory. With respect to the first motive, practicals are invariably used to illustrate, verify or confirm theories taught in another setting, usually in lectures. In reality, theory and experiment are interdependent and, therefore, nourish each other. Experiments assist theory building and theory, in turn, determines the kinds of experiments that can be carried out (Hodson, 1988). Many educators neglect this interdependency in favour of a primacy of either the theory or the practical. Consequently, practical work in conventional courses is usually subservient to theory, is poorly related to course objectives, and consists of exercises for developing manipulative skills rather than assignments for learning to think systematically.

With regard to the second motive, teachers often assume that the practical is the best, if not the only, way to achieve meaningful learning in the Natural Sciences. Indeed, they frequently equate reception learning with rote learning and discovery learning with meaningful learning, seeing it as a one-dimensional continuum, despite Ausubel's insistence not to do so.

> The distinction between rote and meaningful learning is frequently confused with the reception-discovery distinction... This confusion is partly responsible for the wide-spread but unwarranted twin beliefs that reception learning is invariably rote and that discovery learning is inherently and necessarily meaningful... In laboratory situations, discovery learning also leads to the contrived rediscovery of known propositions... Typically, however, the propositions discovered... are rarely significant and worth incorporating into the learner's subject matter knowledge. In any case, discovery techniques hardly constitute an efficient primary means of transmitting the content of an academic discipline. (Ausubel, 1963: 16-17)

Ausubel considered this *rediscovery* to be nothing more than wasting valuable time exemplifying principles which an instructor could present verbally and demonstrate visually in a matter of minutes. He noted that teacher and textbook had a primary role in the transmission of the content of science, the substantive structure, and assigned the primary role of transmitting the method of science, the syntactical structure, to the laboratory (Ausubel, 1968).

As far as the third motive is concerned, the problems are fourfold. First, the acquisition of understanding demands a rich educational environment. Without a good conceptual framework, meaningful observation, which includes the interpretation of those observations, cannot take place at all. If learners do not know what to look for, the chance is very small that they will see what they ought to see, and even smaller that they will realise that they must interpret it in a particular way -- if indeed they are capable of interpretation at all. Hodson (1988) is even more vehement about this, stating that it is theoretical understanding that gives purpose and form to experiments. Second, scientific theories are for the most part *abstract*. They deal with theoretical concepts and their interrelationships. Science teachers "conveniently forget" (Hodson, 1988) that many aspects of the science they teach are not susceptible to direct experimental study. Students are misled and their thinking is restricted when everything is supposed to relate to laboratory experience. Third, reality tends to clutter and distract. Students engaged in practical work often get so embroiled in the details of what they are doing that they miss the underlying concept they were supposed to be studying. Fourth, the amount of experimenting and practice necessary to make enough observations to distil insight and understanding is so large, and would require so much time, energy and resources (both physical and monetary), that the goal is unachievable. An experiment may provide a demonstration of a concept, but it is only one, single demonstration. A learner, even a brilliant or highly gifted one, will not be able to derive meaning from a single instance of a phenomenon. In most cases, the formation of a concept requires multiple exposure to a wide range of instances.

These three faulty motives (illustrating the theory, achieving meaningful learning and distilling insight into natural phenomena) are based on the notion that because scientists discover new aspects of the substantive structure of science through practising science, the teaching of this substantive structure should be done in the same way. In our view, teachers should not ask students to `do science' so that they will discover or rediscover facts, principles, laws and theories the way scientists discover them. Rather, they should teach students about `doing science' and through the use of practicals.

Valid Motives for Practical Work

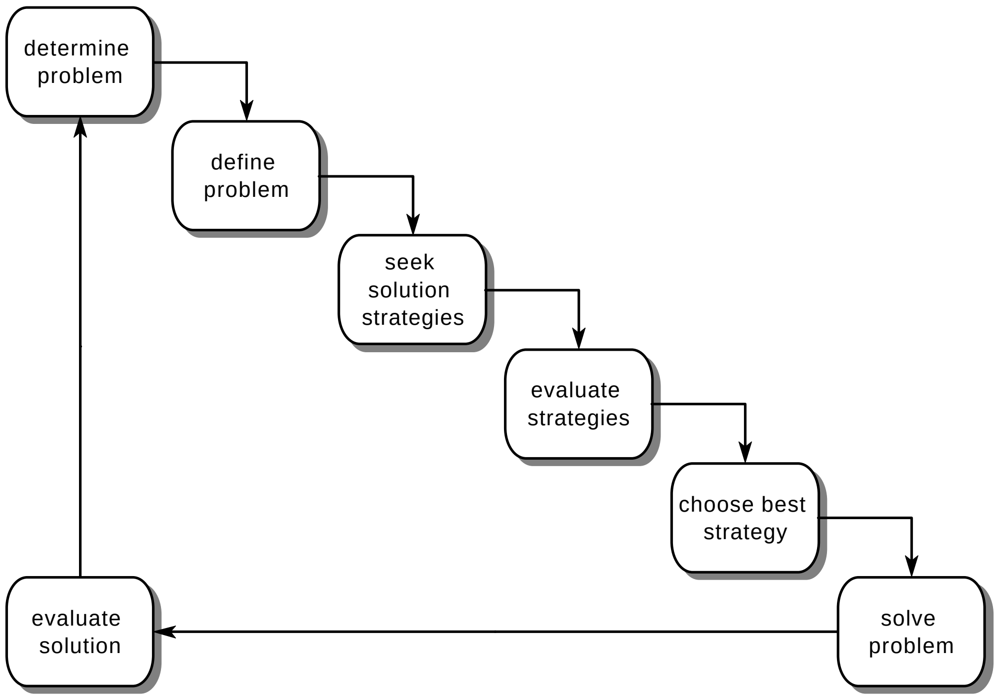
Practicals are better suited to introducing students to, and helping them to become proficient in, the syntactical structure of scientific knowledge. This premise brings with it three new, more valid motives for implementing practicals in science education.

- Teaching or learning the academic approach to working, especially as a scientist.
- Helping students develop specific skills.
- Allowing students to experience phenomena and to achieve some tacit knowledge of them.

Motive 1: Working As An Academic

Practicals are suitable vehicles for learning the `academic approach' to working, especially as a scientist. Woolnough (1983) calls this the use of practicals as *investigations*. Scientists, in common with all academics, are problem-solvers. Their method of working entails a cyclical process of at least the following skills:

- Studying a situation and acknowledging that there is actually a problem to be solved
- Defining the problem to be solved
- Seeking alternative solutions/solution strategies for the problem
- Evaluating the alternative solutions/solution strategies
- Specifying or choosing the `best' solution strategy
- Solving the problem
- Evaluating the solution and determining whether a new problem need be acknowledged, in which case the cycle begins again



Expository substantive knowledge, gained in the cognitive phase, is a prerequisite for attaining the desired ends. In other words, before one can do something with knowledge (act upon it, act with it, modify it and create new knowledge), one first has to have it. Each of the steps in the diagram above presupposes the possession of knowledge, including knowledge of methods and techniques, knowledge of one's own domain (theories, principles, concepts and facts) and of related domains. In simple terms, one must acquire a broad critical knowledge of the subject matter, the learning of basic competencies, prior to successful, productive and useful scientific enquiry. Subsequently, one can learn to synthesise concepts rationally, enquire scientifically and solve problems via unrestrained inductive thinking (Kyle, 1980).

After having gained the necessary prerequisite substantive knowledge, students need to be placed in situations where they have to make use of that knowledge in carrying out the tasks associated with scientific inquiry. Practicals provide an opportunity to develop competence in learning to investigate and in learning to solve problems. Further, the chance for students to discuss, reason and compare what they have done with other students (or via an inter-active electronic medium) is a necessity for attaining these (sub)skills. The `experimental seminar', because of its frequent use of discussion, is particularly well-suited medium for the achievement of motive 2. In experimental seminars, students co-operate in the performance of an experiment or watch an `expert' perform one (Conway, Mendoza & Read, 1963). The subsequent group discussion, where necessary stimulated by an `expert', enables students to help each other gain a clearer understanding of how a well-performed experiment progresses. Interestingly, an experiment which is routine and uninteresting to one or two students can sometimes trigger a valuable discussion in a group. The opportunity to model, discuss, reason and compare methods and results with others assists students in building meaningful and authentic understanding. In other words, it assists them in refining their understanding of: problem identification; experimental design; assembling, testing and calibrating equipment; data collection; analysis; interpretation; and reporting of results.

Motive 2: Developing Specific Skills

The principal sub-skills for independent scientific work that can be developed through practical work are: discrimination, observation, measurement, estimation, manipulation, planning, execution and interpretation. Their attainment is based on two simple underlying principles -- practice and feedback -- and presupposes the attainment of relevant skills and knowledge in the cognitive or declarative phase. In other words, the practical is not subservient to the theory but is complementary to it.

Greeno (1978) suggests that strategic planning, *metareasoning* as he calls it, is central to scientific problem-solving. Metareasoning is the capacity to reason about one's reasoning and includes the ability to assess and revise one's own understanding. In order to gain metareasoning skills, extensive practice in designing various approaches to problems and frequent feedback as to whether these approaches are successful are essential. Simulation is, of course, particularly well-suited to the development of these skills because it allows poor designs to be followed and their inadequacies discovered, modified or eliminated, quickly and safely. This is often not possible with experiments. First, because allowing students to follow a poor design could be dangerous. Second, because experiments can become so complicated that students are unable to identify their mistakes. Moreover, simulation takes much less time than `real' experiments, thus allowing for increased practice and increased feedback. Simulations also allows the teacher to tailor the learning experience, decrease and increase complexity, include or exclude certain features, adopt `idealised conditions' and in general create an experimental situation that enables the learner to concentrate on the central concepts without the distractions, waywardness of materials and `pedagogic noise' that is so much a feature of experiments with real things (Hodson, 1988). In other words, student and teacher can explore specified microworlds without the normal constraints imposed by laboratories, and unforeseen data, artefacts and measurement errors can be added or eliminated, depending on the teacher's objectives. Finally, by eliminating concrete experiences, and providing instant feedback on the appropriateness of certain speculations and predictions, (computer) simulations enable learners to spend considerably more time manipulating abstract ideas as a way of building understanding.

Motive 3: Experiencing Phenomena

The third motive for implementing practicals in science curricula is to allow students to experience phenomena. The motive is not to gain theoretical insight or understanding of phenomena, the rationale for practical work criticised and rejected earlier in the article, but to get a `feel for phenomena' and is best characterised by the German word *Fingerspitzengefühl* (literally, to feel it in one's finger tips; figuratively, to be intuitively aware of or ‘to feel it in one's bones'). It is the gaining of an implicit, often indescribable or tacit, feeling or awareness of what is happening or what is supposed to happen, as opposed to the explicit knowledge of how or why something works. Familiarisation with the world around us cannot be achieved in any other way.

This feeling or tacit knowledge often cannot be expressed in words, either to oneself or to others, but can be strengthened or directed through discussion with others. Nor can tacit knowledge and skills be fully articulated and systematically taught through formal presentation. Rather, as Smolicz and Nunan (1975: 136) say, they have to be acquired through direct experience in the laboratory with its "verbal, muscular, emotional, as well as intellectual, forms". In common with Lave (1988) and other writers in the field of situated cognition, Smolicz and Nunan (1975: 136) state that such knowledge is best attained "outside the province of the professional educationist... [and] must be left to practising scientists for they alone possess the exemplars necessary for initiation". In other words, science educators need to shift towards a model of learning as **apprenticeship** or "enculturation into the scientific community" (Hodson & Hodson, 1998a,b). `Wet laboratories', hands-on experience in a laboratory setting, are best suited for this goal (Head, 1982). These laboratories can be formal, experimental, or divergent laboratories.

Designing Non-Traditional Practicals

The questions we should ask at this point are not whether practicals should or should not be used, whether they are or are not effective, or whether more or less time should be spent on them. Rather, we should ask:

- Do we want to continue using practicals for the wrong reasons?
- Can we afford, both in terms of lost learning and misused resources, to use practicals for the wrong reasons?
- Are we bold enough to attempt to use practicals in a new and innovative way?

The remainder of this article asks: `What are the objectives that educators should attempt to achieve through practicals?' and `Which types of practicals should they use to achieve them?' Much of the discussion focuses on computer simulations. It is important, therefore, to recognise the key distinction between their use in science or technology and their use in education (Huisman & de Vries, 1991). In the former, the theoretical model embedded in the computer program is explored in order to find the consequences of hypotheses that are formulated in the model, or is used to predict the behaviour of the modelled system (e.g. the weather). By contrast, educational simulations are defined by Huisman and de Vries as "interactive learning environments in which a model simulates characteristics of a system, depending on actions made by the student". The major difference is that science simulations are designed for effective simulation of phenomena and events to aid further theory-building, while educational simulations are designed to facilitate effective learning of the underlying model. In addition, to be educationally effective, a simulation should contain some form of guidance. Without it, an educational simulation program is no more than a computer game.

Typically, the use of simulations is advocated when: (1) the `real' laboratory is unavailable, too expensive or too intricate; (2) the experiment to be carried out is dangerous for the experimenter or the object of experimentation;

(3) the techniques which need to be used are too complex for the typical student; and (4) there are severe time constraints. However, each rationale regards simulations as a surrogate for `real' laboratories; none view the simulation as a viable practical form in its own right. What follows is a rationale for the use of simulation that is independent of these laboratory-surrogate benefits. Furthermore, most literature about simulations in science practicals concentrates on `non-educational' reasons for using them, such as cost, time, safety, motivations, control, management, and so forth (see for example Scaife & Wellington, 1993). The discussion here focuses on the significance of good design considerations. As the saying goes: if something is worth doing, it's worth doing right!

1. Replacing traditional practicals

Once the difficult decision to replace a traditional lab by computer-based activities has been made, the redesign process may follow one of three extreme scenarios, depending on the extent to which the staff are familiar with the principles of instructional design.

In the first scenario, the computer is seen as a panacea that will solve problems simply because it is a new medium. A **programmer** is asked to develop a computer program, preferably multimedia and/or over the Internet, by which students can carry out the practical on the screen. Together with a (junior) content area specialist, the programmer starts making pictures of the laboratory setting, building an Internet site with frequently asked questions, scanning texts for inclusion in a database and enriching them with hyperlinks to additional background information. After some time, an instructional designer is asked to investigate whether the new approach is more effective than the old and/or to make suggestions on further improvements of the computer practical.

In the second scenario, those responsible recognise that a shift to another medium will also have educational [1] consequences and so invite an **instructional designer** to design the computer version of the practical. The instructional designer analyses the apparent objectives of the existing, traditional practical and tries, together with the programmer and the (junior) content specialist, to construct a computer practical that aims to reach the same objectives.

In the third scenario, it is assumed that the traditional practical is in one way or another inappropriate. An instructional designer is invited to analyse the situation and identify ways to improve it. The instructional designer determines that, on the one hand, the staff is hardly able to formulate the objectives of the practical at all and, on the other hand, that the original practical often does not allow students to achieve these objectives anyway. Moreover, in the discussions with the staff, it turns out that the supposed objectives of a specific practical have very little relationship with the goals of the curriculum as a whole. For example, while the curriculum rhetoric often espouses high level cognitive objectives, practicals often focus on fairly low level manipulative skills.

These three scenarios demonstrate the difficulties that may arise when a traditional practical is to be replaced by an electronic one. In the first scenario, a one-to-one copy is made, though it is uncertain whether it will be any more effective than the traditional approach. In the second scenario, a functional copy is made, though it focuses on the same (often trivial) learning objectives. In the third scenario, at least initially, nothing is made at all, though the instructional designer poses irritating questions relating to the purposes of science education. In all three, it is uncertain when the project will be finished, or whether a finished product will be in any way superior to what is replaced.

2. Adapting other materials

Many non-traditional (computer) practicals are initiated because the content area specialist for a course imports practice from research or applied science. In fact, most of the more complex educational simulation programs are built around a pre-existing model or database designed or developed for research purposes, simply because developing such a model or database for educational purposes is far too expensive. From the designer's perspective, this adoption process is a somewhat uncomfortable one. As in scenario one, above, much work has already been done without any explicit instructional design or intention for educational use. Moreover, such scientific simulation programs tend to be the result of years of research by several people, which often means that their implicit design is a compilation of adaptations and ill-documented `fixes' with little coherence. Adopting and adapting such a program for use in education is difficult; it is very tricky to make alterations in the original source; a lot of effort is needed to help students understand the peculiarities of the program so that they are able to work easily with it.

3. `Starting from scratch'

In this, our preferred approach, the principles of good instructional design are paramount, though problems still intrude. For example, in practice, an instructional design is often asked for *after* the concrete decision to use a computer has been made. This tendency is reinforced by the trend towards `innovation incentives', such as subsidies and grants, and by a climate in which `introducing new technology' is regarded as synonymous with `educational innovation' (which in turn is synonymous with `improvement'). Language, especially new terminology, can play a key role, too. A proposal for a computer-aided learning program has less chance of getting funded than a proposal for `a multimedia environment', a CDROM, or an Internet application. In our view, medium choice should not come at the beginning, but at the end of the instructional design path. The scheme below shows such a path. It is an abridged and somewhat modified version of the production method for interactive learning environments developed by Koper (1995).

Scheme: scenario choice

Activity	*Level*	*Characteristics*
1. Define curriculum	Curriculum	· End terms (curriculum objectives); · Subject area or domain; · Target group
2. Split into modules / define all courses	Course	· Course (general) objectives; · Subject matter; · Target group(s); · Starting conditions; · Expected course use
3. Define all tasks that students need to do to meet the course aims.	Task	· Specific objectives; · Didactic functions; · Specific subject matter
4. Define alternative ‘didactic scenarios' that will bring the student to perform the task	Didactic scenario	· Objects, actors, functions, media; · Degree of didactic appropriateness; · Costs (time/money; student/institution); · Benefits (time/money; student/ institution); · Production and exploitation aspects
5. Choose the best scenario...	...based on:	· Means of student · Means of institution · External factors

In our recommended approach, the designer tackles the traditional media choice problem not by choosing between alternative media, but between alternative `didactic scenarios' --fairly exact descriptions of the way (means, tools, rules, processes) an educational task is to be accomplished. Thus, the first step in the instructional design process is to answer the question: `Why is this task needed?' In other words, what are the true objectives? Next, an answer must be found for the question: `What should happen when the task is being performed?' In other words, should the student practice, apply, be motivated, be assessed, or whatever? And how should this be accomplished? The third question is: `How should this be done?' It is tempting here to think in terms of media, and their strengths and weaknesses, but it is better to concentrate on the *objects* and *actors*: `Who or what should do what?' This question can, to a large extent, be answered irrespective of the medium eventually chosen.

The description of a coherent set of objects, together with their functions, medium usage, communication channels and supposed behaviour is called a *didactic scenario* (Koper, 1995). Essential to good design is the formulation of several didactic scenarios. These may differ in many aspects (objects, media choices, guidance, even subject matter, effectiveness, efficiency, etc.), yet still accomplish the same task. For each alternative scenario, the costs, benefits and production aspects must be made explicit as a factor in the decision process rather than as a limiting condition. Also, the expected lifetime of the innovation should be taken into account, especially for network programs and multimedia programs that depend strongly on standards with only short term predictability.

The final selection should be based on the characteristics of the scenario in combination with the means of the student and the means of the institution. Sometimes, external factors play a role -- for example, a preference for information technology solutions because of the supposed spin-off to other projects. The outcome of the scenario choice procedure may be that the task can be achieved solely with printed materials. In distance education, this is often the case. The choice for other media should be based on the expectation that they add necessary value (i.e. achieve aims that printed materials cannot achieve). For practicals, the outcome is almost always a `media mix': even a completely self-contained computer-based tutorial is often introduced on paper or by a tutor. More typically, background information is given on paper, further reading is accessed via Internet, simulation is done on the computer, reports are written alone or in groups of students, and assessment takes place via a human tutor.

Even with the advent of multimedia computers, it is still important to follow the full scenario choice procedure. Although text, audio, video, interaction, animation and simulation can be combined on one CDROM, it is necessary for design purposes to know *what* should be on video, audio, written text, etc.. Moreover, a CDROM cannot replicate some of the more valuable features of traditional learning environments (the stimulus and interactivity afforded by fellow students and tutors, for example) nor can it capture the richness and dynamism of the Internet.

In the harsh economic realities of the 1990s, the development and maintenance costs of alternatives to traditional practicals cannot be ignored, though direct comparisons with `Wet lab' costs are not easy. In a traditional practical, the initial production costs are low [2] and the exploitation costs are high. The exploitation costs are more or less linearly coupled to the number of students -- that is, the number of staff necessary for preparing, running and evaluating the practical. In a computer practical, production costs are high and exploitation costs generally low. Exploitation is then the maintenance of computers at a study centre or delivering the software to students at home and supporting them when problems arise. Some CAL programs are satisfactorily used for up to 10 years; students readily accept an old-fashioned look-and-feel [3] if the educational benefits are obvious.

With multimedia, the picture is becoming less clear. Multimedia programs use standards that tend to change rapidly without downward compatibility. In the past ten years, the analogue laser-vision video-disk displayed on a video monitor has been replaced by the same disk but displayed digitally on a computer monitor, which has since been replaced by CDI , which has now been replaced by MPEG-1 on CDROM. This means that within just ten years four technical revisions have been necessary. Moreover, the typical production time for an educational multimedia program is about three years, which is equal to the turn-over time of the hardware and its standards. In other words, at the beginning of the project one does not know what the exploitation environment will be. Therefore, multimedia have a difficult-to-calculate production risk that should, nevertheless, be weighed seriously in the media choice.

Examples of Dry Practicals

It is tempting to construct a taxonomy of types of `dry' practicals based on aspects such as whether an underlying theoretical model is involved, whether the student designs the experiment, whether an electronic tutor interacts with the student, and so on. In practice, however, nearly all simulations are mixtures of several idealised types, aimed at mixed learning goals, using several media. We have therefore chosen to present examples of a number of dry practicals, each with one or two interesting aspects of their design highlighted. All these programs are used in the science curriculum of the Open University of the Netherlands [4]. Taken together, they give a better idea of the variety of ways in which educational computer programs -- or computer-based educational programs -- can be used to help students reach the objectives of higher science education.

<u>1. Interactive Case Study</u>

LAVI-leed (Huisman et al, 1993) exemplifies how financial considerations can force a decision to make a text-only program rather than a multimedia package. In an introductory course on environmental science, students needed to be confronted with the reality and complexity of environmental problems. They needed to experience the dilemmas of the environmental scientist and to apply theoretical concepts learnt from the texts. For this purpose, an `interactive case' was conceived in which students follow a game-like structure, through which the case evolves according to decisions made by the student.

In such a confrontation, video and audio are often used for introductions, visits to the case site, explanation of experiments and interviews with experts. However, most students in the target group did not have multimedia computers at the time the program was being designed and so such a program would have required multiple visits to a university study centre. It is our experience that most distance students will do this only if the program use is mandatory (i.e. a written report is required and will be marked as part of the assessment procedures).

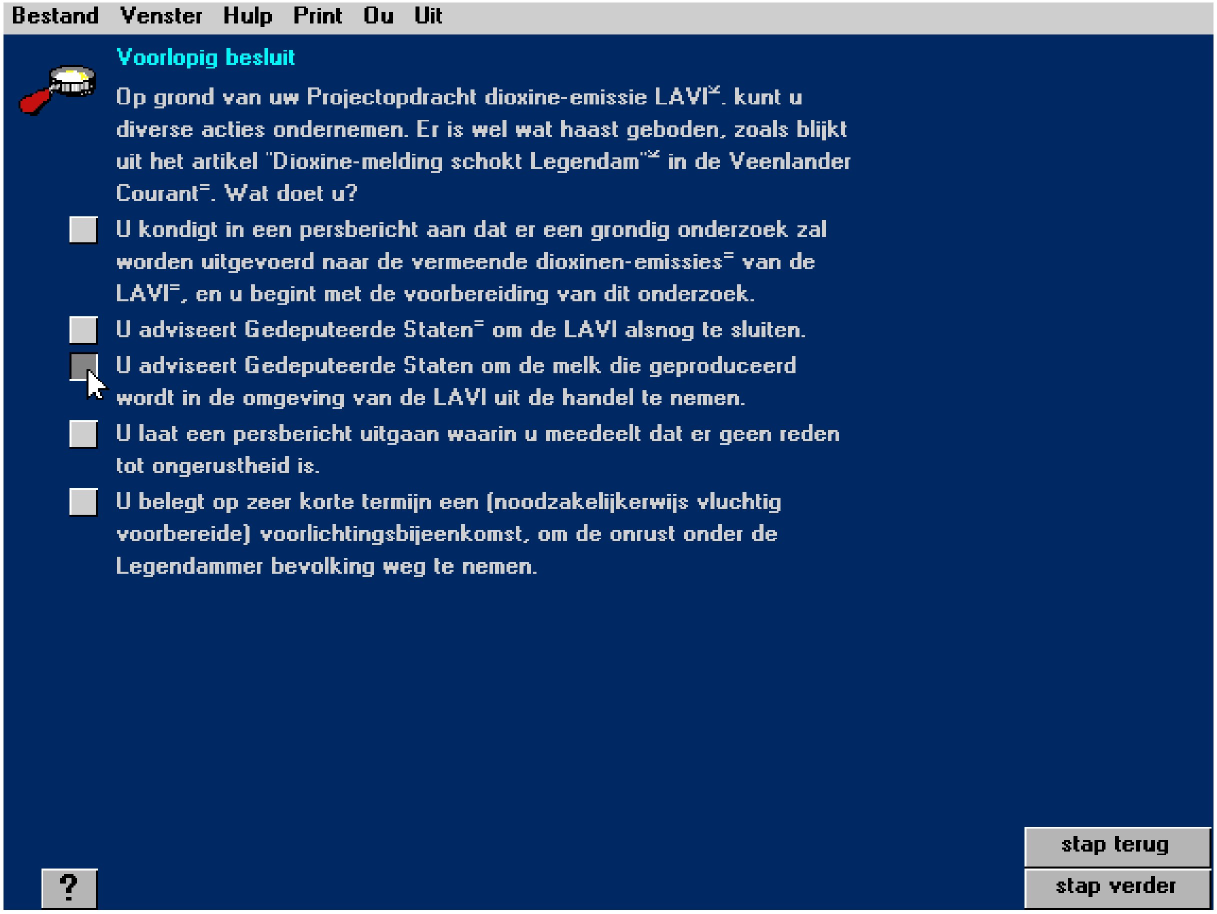


Figure 1 LAVI-leed: A screen from the "multimedial" text-only practical LAVI-leed in which students choose between a number of actions in an interactive case on environmental policy. Although this screen is quite straightforward, there are two types of hot words which initiate hypertext links to resource texts and a dedicated dictionary.

This being an introductory course, a large number of students was expected and staff marking would be too costly. On the other hand, our experience is that students who receive a diskette that will run on their own computer generally do install the program and use it. Therefore, it was decided to select a case that could reasonably be presented and studied by means of (interactive) text. The result is a relatively simple but adequate program that is effectively studied by a large number of students.

2. Handling Information Overload

Bodem en Milieu (Soil and Environment) (Lansu et al., 1994b) is a multimedia program that presents students with a large volume of diverse, sometimes contradictory resources on three cases about soil and environment.

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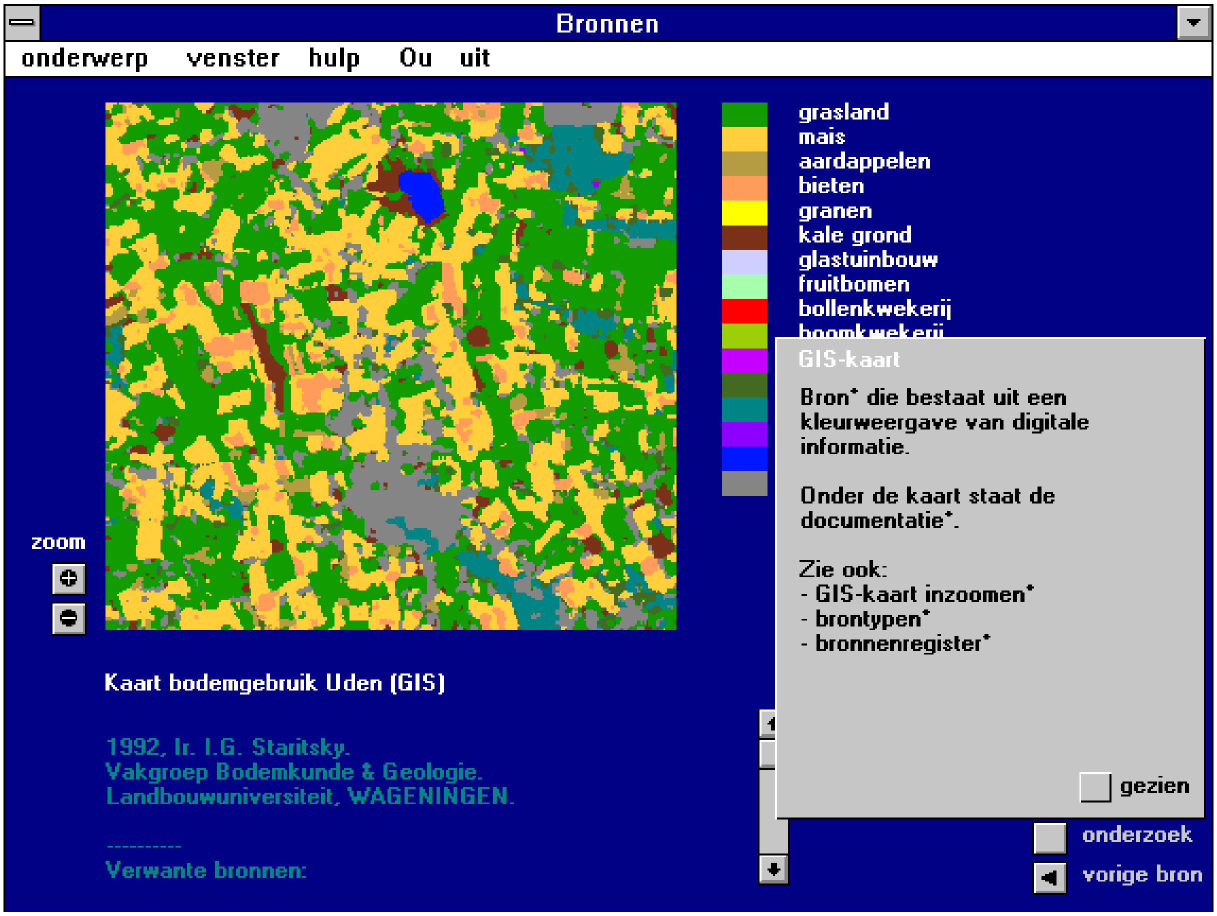

Figure 2 Bodem en Milieu: A map from a Geographical Information System is one of the numerous source materials in the practical Soil and Environment. Although no GIS itself is available in the program, a large number of processed GIS maps can be accessed easily.

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While developing the program, two major difficulties occurred that are of interest in the context of this article. First, it appeared nearly impossible to teach students how to systematically carry out such a case study. The content area specialists could only specify a fairly rough method of working, consisting of an `orientation phase' and several content-specific phases. In fact, most of the resource selection appeared to be a largely intuitive process. Therefore, it was decided that the students should learn to handle the resources by *doing* -- in fact, by trial and error. In the first of the three cases, guidance is given in the form of a phase structure, and resources are presented in relation to these phases with some feedback on the actions the student performs. In the second case, guidance is only at a basic level, and in the third case, there is no guidance at all, except for a tutor feedback on the final report (grade plus comments on the report).

The second design difficulty concerns the media choice in combination with the didactic decision to present the student with a study environment (Hummel, 1993; Lansu et al., 1994a) that would be as authentic as possible. Authenticity was taken quite literally: resources were to be shown as they were in reality -- which, for some resources, was ill-documented, hardly understandable, and barely readable. Not at all the quality that students are accustomed to in their university learning materials. However, once the laser video disk was ready, it appeared that the resolution on the computer screen was insufficient to show images that were not especially formatted for it. The end result is a mixed representation of sources, some original, some brightened or enlightened, some completely new, with students still complaining about the lack of clarity. In the new CDROM-version, some of the true original sources will be available in print.

3. Designing An Experiment

In the practical *Behavioral toxicological research* (Niesink et al. 1997: Program references), students are given a laboratory in which they learn to design experiments. They analyse research questions, formulate hypotheses, search literature, set up an experimental protocol and analyse/interpret experimental results. Much effort has been invested in the early phase of research: translation of a research question into a testable hypothesis. Students enter their formulation of the hypothesis in full text. An intelligent procedure interprets this and comments on unknown or wrong elements until the student has amended and reformulated the hypothesis into an acceptable form. Based on the hypothesis, students set up an experimental protocol by choosing between a large number of options on methods, materials, techniques and parameters. A built-in tutor comments on the relation between protocol and hypothesis. Students do not perform the experiments: results are drawn from a database and are presented for analysis and interpretation. This interpretation, again with the aid of the electronic tutor, takes place on two levels: (i) Is my hypothesis confirmed or rejected? and (ii) Is my experimental design appropriate?

In the design of this program, there was a tension between the desirability of maximal freedom for the student and the limited capabilities of the database with experimental results. `Maximal freedom' is a didactically-based decision to force the students to think creatively instead of choosing between alternatives. Ideally, the `laboratory' should support **all** experimental design decisions and allow their performance. In practice, the variety of possible protocols is so large that even with a combination of database and simulation an enormous program would be needed to yield appropriate experimental results. Therefore, in each of the phases of the research, a filtering takes place that rejects designs leading to experiments for which no results are available.

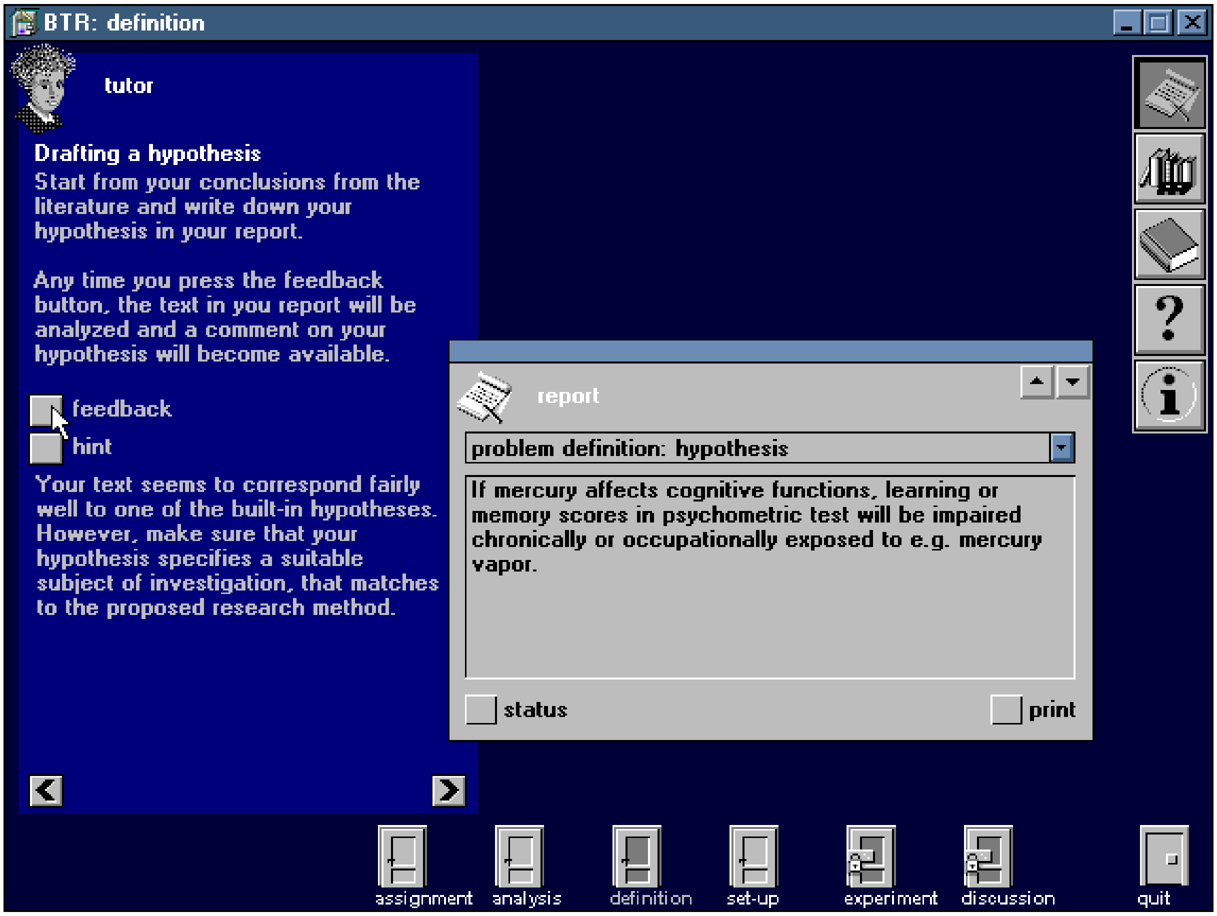

Figure 3 Behavioural Toxicological Research: Formulating a hypothesis is an important step in the research process. The student should enter a hypothesis in free text. It is commented on by the electronic tutor until the student has produced an acceptable hypothesis.

This filtering is performed at three levels: (i) obviously erroneous decisions are rejected; (ii) decisions that do not relate to the research question or to the hypothesis are rejected; and (iii) decisions for which there is no experimental data are rejected; all, of course, with appropriate explanation. In both the field testing and in actual use, students understand and appreciate the necessity of these limitations.

4. Understanding Ecosystem Processes

Oosterschelde (Huisman et al., 1991) is a typical example of an educational simulation program. It is a program built around a large scientific model that simulates the ecological behaviour of the *Oosterschelde* estuary in the Netherlands. The 25-hour practical aims at learning on three levels: insight into ecosystems, insight into ecosystem modelling, and insight into computer techniques used in modelling.

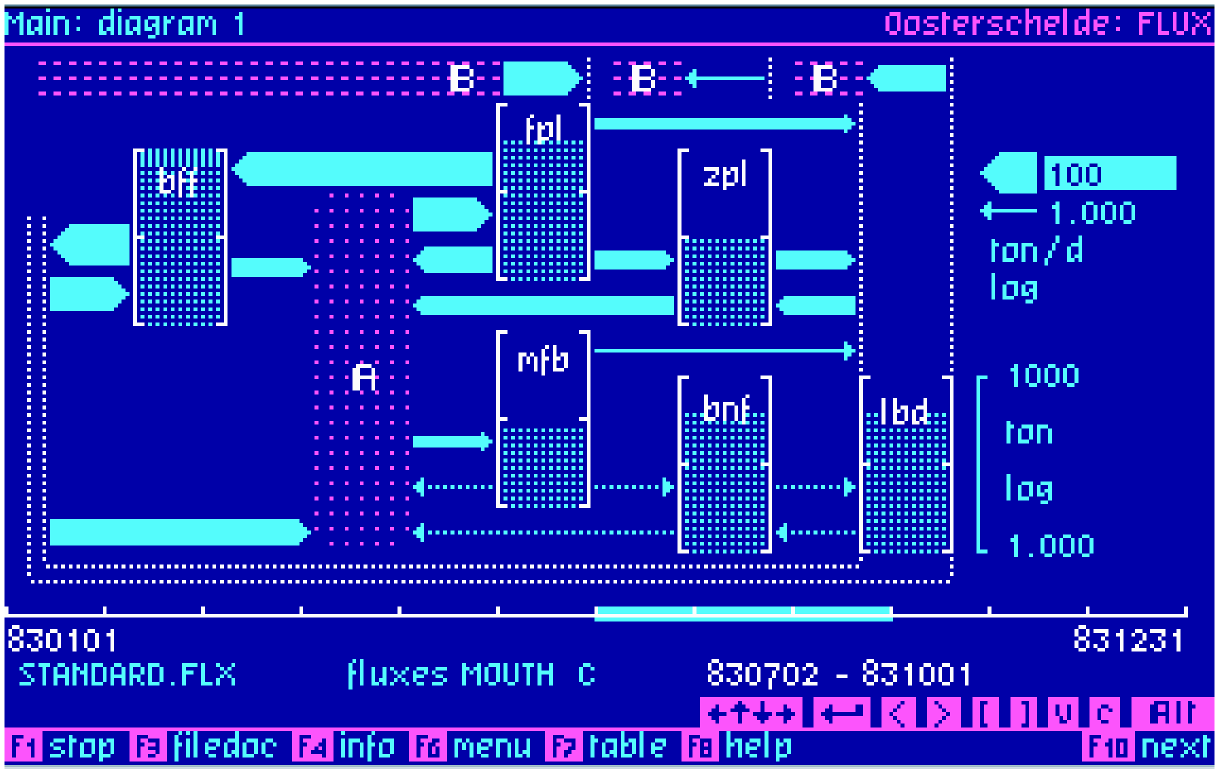

Figure 4 Oosterschelde: A screen from the practical Oosterschelde. The main processes that determine the ecosystem (and therefore the model) are carbon fluxes and transports. Students are encouraged to study this diagram thoroughly. The effect of time on the system can be seen 'animated' by sliding the blue horizontal bar along the time scale.

For all three levels, *Oosterschelde* functions as a case study: it is one program that runs one model of one ecosystem. Accompanying printed texts put the case into the context of other ecosystems, models and programs. An interesting design aspect of *Oosterschelde* is that students study it `upside down': they start with a thorough analysis of standard output of the model. Only at a later stage, do they follow the normal procedure of modifying input and running new simulations. One reason for this reversal is the complexity of the model, which makes a sub-program on model input incomprehensible without a basic overall knowledge. A more didactic reason is that the model output gives a good representation of the ecosystem. By studying the model output, the student studies the ecosystem itself. The traditional way to represent output of dynamic models such as this is via graphs of state variables as a function of time, optionally together with corresponding measurement data. Such graphs, however, do not directly represent the basic processes in the ecosystem: the fluxes and transports of matter. If students are to understand the system, they must first study these processes. Therefore, a sub-program was built that represents the modelled processes as flows and measuring glasses, with a number of tools to identify, scale, average, normalise, and compare them.

In simulation programs, it is very easy to define combinations of input values that will lead to erroneous results. The design question is, `To what extent should students be protected from this `garbage in, garbage out' and the confusion that may result from it?' It is quite tempting to protect students in the phase where they define model input so that the output will be a reasonable representation of reality. However, in *Oosterschelde*, it was explicitly decided not to do so, both for practical and didactic reasons. The practical reason is that it is impossible to foresee the effect of input combinations. If, for example, a student changes two input variables within their realistic range, the combination may be nonsense. And *Oosterschelde* uses some 500 input variables! The didactic reason is more important. Students at this stage in the curriculum should learn to do systematic `what-if?' analyses with large models, being aware that all models have restricted validity. Moreover, because one of the aims of the practical is to let students experience the full complexity of an applied research model, it would be illogical to construct protecting limitations.

A third issue is the method and the level of guidance (Huisman & Westerterp, 1994). In *Oosterschelde*, guidance ranges from simple questions on keyboard usage to complex, day-long assignments on environmental problems. Here again, a radical decision was made: the program presents no guidance at all unless the student asks for it. `Asking' can be pressing a hot key for help on key usage, pressing another key for advice, using hypertext to use the built-in dictionary, searching a menu-structure with most of the documentation on the original model, and so on. The course books provide students with a range of assignments of varying background and interest from which to choose. Finally, a tutor assesses and grades the final assignment.

5. Testing and Justifying Scenarios

Wasmeer (Huisman et al., 1986; Huisman, 1989) is a four hour practical on ground water pollution control located in the very first course in the environment curriculum. It is of interest here because it is, in many respects, the counterpart of *Oosterschelde*. It is also a true educational simulation program, with completely integrated guidance.

Figure 5 Wasmeer: A screen from the practical Wasmeer showing the drop in groundwater-level as a result of pumping. Despite the old fashioned look-and-feel of this practical, dating back to 1984, it is still in use.

At the time the program was designed (1984), most students had no experience at all in working with a computer. Therefore, the program is essentially a built-in tutor, taking students by the hand and leading them through seven levels of complexity. On each level, aspects of the environmental problem, ground water physics, modelling, and computer usage are dealt with. At the seventh level, students master the usage of the simulation model -- of which the input variation is restricted to only this specific case on ground water control. Students define and test different scenarios and write a report, which is marked and commented on by a live tutor.

A peculiarity of *Wasmeer* is that, despite its quite old-fashioned look and feel, it is still being used and, more importantly, it is used in a way for which it was not designed. Although designed for use by single students, it now plays a satisfactory role in introductory face-to-face meetings where students work in pairs and discuss their final scenario in a larger group. Thus, the program serves as a shared and quite easily achieved basis for a fruitful discussion between students, aiming more at social and communicative skills than at cognitive skills.

6. An Impossible Field Experiment

Weegbree (van Dijk et al., 1988) is an educational simulation program that uses the metaphor of a traditional field practical for an experiment that is conceivable, but in reality impossible. The student selects plots of land in a predetermined environment near a dike or in a self-defined environment in an experimental garden, and then sows `idealised' seeds of *Plantago*. Over the next `25 years', a number of environmental variables, such as winter severity and flood duration, together with population characteristics (number of seedlings, flowering time, and root weight), are `measured' at all selected plots. Thus, the experiment follows the combined effect of natural selection and chance, leading more or less realistically to the formation of the various ecotypes of *Plantago*.

Weegbree, like *Oosterschelde*, has learning goals at three levels. The first level is that of defining a field experiment and statistically analysing the results, and then redoing the experiments. The second level is that of interpreting the results in relation to course book knowledge about the principles of genetic drift, fitness, adaptivity, migration and selection. The third level is that of understanding the model that `performs' the experiment -- in fact, a relatively simple population genetics model in which these evolution principles are quantified.

7. Interpreting Histological Changes

Changes in tissue morphology produced by toxic agents are generally determined by comparing carefully stained microscopic sections of exposed and unexposed tissue. In biomedical education, these microscopic sections are often replaced by slides that are shown and commented on in a lecture by a tutor. This practice substantially reduces the costs and effort of letting the students inspect the sections for themselves and avoids the many inevitable misunderstandings from misjudging artefacts, or just looking at the wrong histological structures. However, such a tutored slide-show has the great disadvantage that students are put in a passive position, merely following the tutor and trying to keep in mind all that is said and shown.

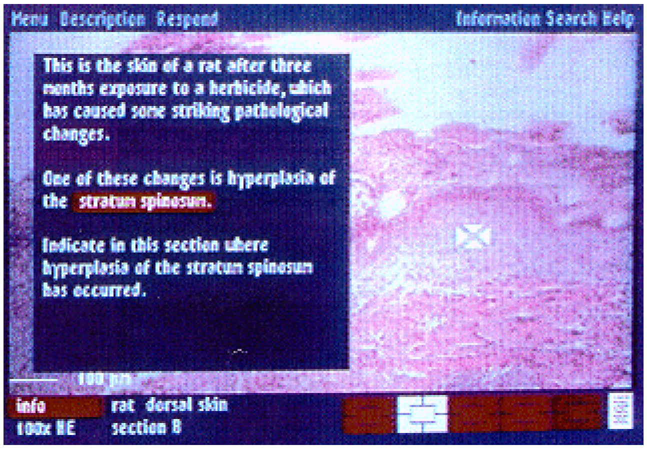

Figure 6 Practical Toxicological Histopathology: Screen photograph of a program section in which the student is invited to indicate toxicological phenomena by pointing with the mouse pointer. The program will check whether the correct spots are indicated.

The practical *Toxicological Histopathology* (de Vries & Niesink, 1991) gives students a more active role in determining the effect of toxic agents on tissue. In the practical, electronically available slides are shown in various magnifications, accompanied by comparable slides of unexposed tissue. There is an archive of thousands of other slides of different tissues, affected by the same or different agents, in different concentrations, from different animals, with different stains and different magnifications obtained from different types of microscopes. Now, an electronic tutor is not explaining phenomena, but posing questions, which the student has to answer by observing the slides, reading background information, viewing slides of other pathological effects, and analysing the similarities/differences, synthesising possible explanations and evaluating those explanations. After the student has tried to answer, feedback is given both in text and by highlighting the structures in the slides where the effects can be seen.

The history of this practical reflects the history of visual representation in educational technology, with all its problems. The first step, from microscopic sections to slides, meant an enormous reduction in costs. However, it also reduced the learners' activity by shifting from practical to lecture. The second step, from slide to stills on a videodisk with an electronic tutor, reintroduced student activity, albeit at the cost of a serious investment in building the program and the videodisk. The need for students to do the practical in the study centre, in order to access the necessary equipment, was a disadvantage. Ideally, the various effects should be studied at the moment they are encountered in the course book, which covers a 120-hour studying period. Therefore, in a pilot project, a CDI version was made, which at that time promised to bring multimedia at low prices to the student's home (de Vries & Niesink, 1991). It is now clear, however, that CDI will not penetrate the market and that a CDROM would be a more suitable replacement.

8. Collaborative Learning

This practical, which is the major part of a basic course on geographical information systems (GIS), has learning goals at two levels: objectives related specifically to the subject matter; objectives related to general academic skills in the wider curriculum (motive 1, above). Learning to understand a GIS is typically accomplished by using it, in a fashion similar to the way one learns to use and understand a word processor. Thus, all students are required to have access to a modern (full Internet access) computer. This means that student communication, both amongst themselves and with a tutor, can be built into the practical as a structural element for the initiation and structuring of the study, the guidance of the learning process and the presentation of feedback on how the process is progressing. Also, a variety of sources for case studies can be found on the Internet. The practical comes to the student as a CDROM containing a full GIS-program, with introduction, documentation and data files for a number of cases. All assignments, extra case materials, links to external data, and so forth, can be found on course-specific pages on the Open University WWW site, with the news group `rooms' for working together on the university news server. Some of the ‘rooms’ are moderated by a tutor, while others are only accessible to the students themselves.

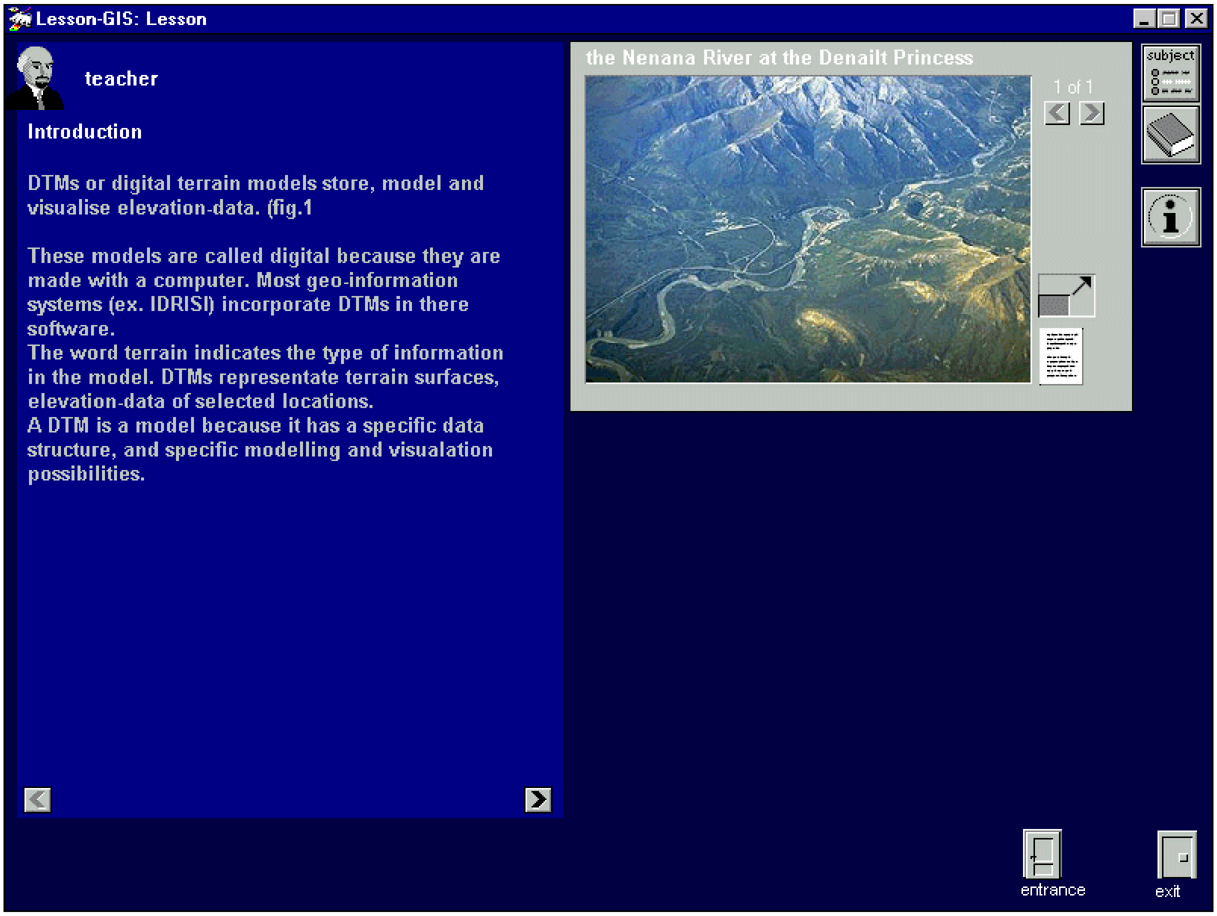

Figure 7 Practical Geographic Information Systems: Preliminary view of a 'lesson' part that gives the first introduction into the program.

With this combined stand-alone computer plus Internet usage, this practical is an example of development at the cutting edge of computer-aided learning. The CAL-practicals of the past 15 years were almost all developed for use by a single student; interaction took place only between this student and various types of professional staff (real life or electronic guides, tutors, etc.). With Internet communication, a number of these guidance and tutoring functions can be taken over by fellow students. In distance education, this is enormously beneficial, not only for the learning process itself, but also for developing the social and communicative skills needed for later interdisciplinary team work. Whether this development will be beneficial for staff depends, of course, on how well the practical is designed, evaluated and redesigned. At first glance, staff save a considerable amount of time previously devoted to development. However, initiating fruitful collaboration and maintaining a proper level of guidance may well turn out to take more time, especially if the interaction between students and staff has not been properly designed and if staff and students have not been properly trained to use the communication tools. These considerations are not restricted to a single practical and need to be dealt with at the institution level. They are, in a sense, the equivalent of good laboratory provision in traditional practical courses.

Concluding Remarks

This article has three goals. First, to make it apparent that electronically mediated practicals in science education have their own rationale, distinct and functionally different from the usual subservient nature of the traditional laboratory practical to classroom instruction. Second, to show that good educational design is an essential prerequisite both for education in general and non-traditional practicals in particular. Third, to present a multifaceted and multicoloured pallet of examples of the uses of computer-based dry practicals currently in use at the Open University of the Netherlands, together with some of the pitfalls encountered in their use.

Notes

1. The Dutch term is `didactic', literally that field of educational science devoted to the transfer of knowledge and skills. In English it has the negative connotation of lecturing others (too much). In this article, we use either `didactic' in the literal Dutch sense, `pedagogic' or `educational'.
2. This costing model assumes that the infrastructure necessary for a practical (labs, apparatus, people, etc.) already exists in the institution.
3. The look and feel of a `wet laboratory' is in many educational settings also either out-of-date or not really comparable to real research labs. Woolnough and Allsop (1985) speak of inaccurate or simplified educational (as opposed to research) apparatus used in undergraduate practicals.
4. Documentation on these programs can be found at http://www.ouh.nl//coo-catalogus. Though the catalogue itself is in Dutch, most program documentation contains an English summary as well as a number of commented screen images. The figures presented in this article can be found at http://www.ouh.nl/open/dry_labs/

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Illustrations:

The illustrations as well as the documentation for the illustrations can be found at http://www.ouh.nl/open/dry_labs