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On developing content-oriented theories taking biological evolution as an example

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Abstract
Both in Europe and the US there is a growing interest in design research. One example is design and validation of topic oriented teaching-learning sequences (TLSs). This research may be said to have two objectives. One is to design and test ‘useful products’, such as teachers’ guides and study material for students, which may be put into practice in various ways. The second is to contribute to the development of educational science, e.g. understanding conditions for learning of given topics under regular classroom conditions. This article concerns the latter objective and deals with the development of content-oriented theories stating conditions that promote learning with long-term understanding of given topics. We present one such theory, concerning evolution by natural selection, and describe the arguments and evidence that underlie the theory, which we regard as a well-founded hypothesis. Some methodological problems associated with testing this type of theory are discussed, as well as the role of content-oriented theories in strengthening science education research as an autonomous specialisation within educational science.
Growing interest in design research

During the last 10-20 years, a growing European interest has been observed in the design and validation of topic oriented 'teaching-learning sequences' (TLSs), such as a particle model for gases or the theory of evolution by natural selection. The state of the art has recently been described in a special issue of the International Journal of Science Education (Méheut & Psillos, 2004). Different ways of presenting and carrying out design work are dealt with, e.g. 'developmental research' (Lijnse & Klaassen, 2004), and 'educational reconstruction' (Kattman, Duit, Gropengießer & Komorek, 1996). Various ideas and principles guiding the design of teaching are also discussed, e.g. 'a problem-posing approach' (Lijnse & Klaassen, 2004), the use of analogies (Schwedes & Dudeck, 1996) and different conflict strategies (e.g. Nussbaum 1989). Methods of studying teaching sequences are also brought up, e.g. pre- and post-tests and descriptions of individual 'learning pathways'.

In the US design is a significant element of educational research. Edelson (2002) claims:

At its heart, education is a design endeavour. Teachers design activities for students, curriculum developers design materials for teachers and students, administrators and policymakers design systems for teaching and learning. If the ultimate goal of educational research is the improvement of the education system, then results that speak directly to the design of activities, materials, and systems will be the most useful result. (p. 119)

Theme issues of Educational Researcher (Kelly, 2003) and the Journal of the Learning Sciences (Barab & Squire, 2004) throw light on both the current discussion in the US and the breadth of the approach, which does not only apply to the design of TLSs, but also to, e.g. software, continuing education for teachers and school organization.

Few references to US design research exist in the European literature on TLSs, and vice versa. Nevertheless, there are several common elements:

- The work is iterative. The design is tested, evaluated formatively, revised and re-tested in several cycles.
- The work aims to contribute to the development of educational science, e.g. by increasing understanding of conditions that favour learning of given topics in regular classrooms.
- The work leads to 'useful products', such as teacher's guides and study material for students that can directly be put into practice in various ways.
- The researcher is seldom simply a researcher, but is also a designer, teacher and teacher-trainer.
- The researcher is directly involved in improving teaching in school.

What theoretical contributions can design research make?

An important question is what theoretical contributions design research might generate in addition to products that are useful to practitioners. This question is not taken up explicitly in the theme issue of the International Journal of Science Education. However, the various authors do make contributions of a theoretical nature. Concerning the US, di Sessa and Cobb (2004) point out that

... theory is critically important but currently underplayed in design research studies. (p. 77)
One type of theoretical contribution has already been mentioned, namely different approaches to how design work in general can be planned and carried out, and can be applied to different contents. Another example is an analytical tool developed by Buty, Tiberghien and Le Maréchal (2004), consisting of a matrix with 3x3 cells. The three rows refer to 'world of objects/events', 'relation between theory/model and objects/events' and 'world of theory/model'. The headings for the three columns are 'already known according to the curriculum', 'already known from everyday life' and 'to be constructed'. By filling in the cells for a given topic, researchers gain a picture of what Leach and Scott (2002) call 'learning demand', which guides further design work.

di Sessa and Cobb (2004) give an example of another type of theoretical contribution, which they call 'ontological innovation'. It is a question of creating new categories through which one can observe the world, e.g. learning and teaching in the classroom, and which can deepen understanding of what is going on. One example of such a category is 'socio-mathematical norms'. These are negotiated more or less consciously in the classroom and refer, e.g. to what an acceptable versus a sophisticated mathematical solution should mean. Such content-oriented norms affect how the students reason and what they learn.

Yet another type of theoretical contribution concerns conditions that promote learning with understanding. This is treated in the following sections of the paper.

**Content specific theories – a necessary complement to general theoretical platforms?**

The science education researcher usually derives theoretical inspiration from sources outside his/her own field, such as psychology and epistemology. One example of a theoretical platform from genetic epistemology is Piaget's constructivist model of 'the knower-known relation'. See Furth (1969) for a detailed description. The educational relevance of constructivism has been summarized by Ogborn (1997) in the form of four ideas:

- The importance of the pupils' active involvement in thinking if anything like understanding is to be reached.
- The importance of respect for the child and for the child's own ideas.
- That science consists of ideas created by human beings.
- That the design of teaching should give high priority to making sense to pupils, capitalizing on and using what they know and addressing difficulties that may arise from how they imagine things to be. (p. 131)

Another starting-point is the socio-cultural approach. A representative of this approach, interested in science teaching, is Lemke (1990). He provides a fair number of recommendations for teaching, e.g.

    Teachers should use question-and-answer dialogue less than they do now and organize more class time for student questions, student individual and group reports, true dialogue, cross-
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discussion, and small-group work. Students should do more science writing during class, always following oral discussion of topics. (p. 168)

One may think that both the constructivist and the socio-cultural guidelines for teaching are neither new nor original but belong to the long-established pedagogical wisdom. But the fact that they emanate from different theoretical approaches may enrich and deepen their meaning in different ways.

Problems with general recommendations

The general recommendations and guidelines described above can contribute to providing a productive direction to our work. But they are insufficient when it comes to designing teaching about a given topic in detail. Take the theory of evolution by natural selection as an example. Teachers and researchers who collaborate to create better teaching within the area ask themselves a series of questions, e.g.:

- How do students explain evolutionary changes, and does this involve difficulties that should be dealt with in a special way?
- How can one get students to think actively and with interest about the various aspects of evolution?
- How can one motivate students to write about evolution?
- How can one deal with clashes between religious beliefs and scientific ideas about evolution?

It is far from trivial to answer these and similar questions. No general theoretical approaches, and recommendations for teaching that follow on from them, succeed on their own in this task. The answers must be sought in combination with content-specific research. The results cannot be deduced from the general approach. They have to be generated, and they will differ, topic by topic.

This insight is not particularly common, according to Lijnse (2000), as far as science education research is concerned:

What seems to be apparent from the literature is that science education research does not aim to develop content-specific didactical knowledge (possibly to be described as 'small-scale theories') but to contribute to (if only by simply applying) general educational and/or psychological theories. I consider this flight away from content detrimental, because thereby a level is skipped that I consider necessary for making a real impact on science education and for making didactical progress. (p. 310)

Dissatisfaction with general approaches is expressed by Cobb, Confrey, diSessa, Lehrer and Schauble, (2003):

General philosophical orientations to educational matters – such as constructivism – are important to educational practice, but they often fail to provide detailed guidance in organizing instruction. The critical question that must be asked is whether the theory informs prospective design and, if so, in precisely what way? (p. 9)

Content-oriented theories

Lijnse (2000) thinks that the primary goal for science education research is content-specific didactical knowledge based on the development of exemplary teaching:
Through reflection on such practices, one might come to formulate content-specific theories regarding the teaching/learning of particular topics, which can perhaps be generalized to a certain extent to similar topics. (p. 312) These theories are expressed in the form of ‘didactical structures’. Lijnse and Klaassen (2004) give different examples. We shall return to this way of formulating content-oriented theories in the final discussion.

Cobb et al. (2003) speak of domain-specific theories:

Design experiments are conducted to develop theories, not merely to empirically tune ‘what works.’ These theories are relatively humble in that they target domain-specific learning processes. (...) A theory of this type would specify successive patterns in students' reasoning together with the substantiated means by which the emergence of those successive patterns can be supported. (p. 9)

We have not found any examples of this type of theory in the area of science in US design literature.

These ideas about domain- or content-specific theories made us realise that some design work that we had undertaken might be regarded as trying to build such a theory of conditions that favour learning with understanding. We had carried out three successive teaching-experiments, consisting of about ten lessons each, with the aim of attaining long-term understanding of the theory of evolution by natural selection. The principles that we use when designing sequences of lessons have been described in a paper by Anderson and Bach (2005). The students (in all 79) were 17 years of age and attended the science branch of upper secondary school. During these experiments we made extensive studies of relevant literature and used various methods to collect information, such as written tests before and one year after teaching, interviews with students before and during teaching, observations in the classroom and video recordings of group discussions. This empirical work has been described in papers (Wallin, Hagman & Olander, 2001; Hagman, Olander & Wallin, 2003) and as part of a doctor's dissertation (Wallin, 2004). The dissertation in particular gives a detailed description of the teaching sequence, of test items used and how pupils' written explanations have been analysed. Information about validity, reliability, and tests of significance are included. The dissertation is in Swedish, but with a summary of 23 pages in English, which is available as a pdf-file (Wallin, 2004).

By analysing minutes from project meetings, detailed lesson plans and field notes retrospectively, we were able to establish content specific aspects that we had taken into consideration in order to favour learning with understanding. Furthermore, we had, during lessons, deliberately discussed the nature of science, among others in order to soften possible clashes between scientific and religious views on the origin of present day biodiversity. We were also aware of having used ideas like Ogborn's four points quoted above. These are not content-specific but general aspects, applicable to many topics and school subjects. Therefore we thought that the term 'content specific theory' was not right on target for our approach to facilitating learning with understanding. Instead, we invented the idea of 'content oriented theory', involving the following aspects:
In the following, we first present the content specific aspects and describe in detail the empirical evidence and arguments on which they are based. After that, we present and discuss in somewhat less detail the other two aspects, whereupon we deal with methodological issues involved in validating the theory. Then we compare our way of formulating a content oriented theory to the one presented by Lijnse and Klaassen (2004) and end up by some reflections on the possible role of content-oriented theories in strengthening science education research as an autonomous specialisation within educational science.

A content-oriented theory for teaching the theory of evolution by natural selection

Content-specific aspects

* Evolutionary time. The space of time during which biological evolution has taken place is almost unimaginable. Dodrik and Orion (2003) point out that there are few studies of how pupils and students perceive this aspect, which is an important element in the understanding of how present-day biodiversity has evolved from simple micro-organisms. The studies that have been done show that pupils and students have difficulty in grasping 'deep time'. See, e.g., Brumby (1981). It is therefore important to illustrate the evolutionary space of time. When this was done with the help of the school's longest corridor, and different events were placed along it according to scale, we found that many students had an 'aha' experience and expressed their appreciation of the activity. Our first point in the content-specific part of our theory is therefore:

1. Evolutionary time (deep time) is made concrete.

* The role of randomness. During our three teaching experiments we have seen various signs that quite a number of students have difficulties accepting random processes. They find it unreasonable that the biodiversity and advanced forms of life that exist on earth should be the result of chance. It is therefore important that the role of randomness is made clear. It is a question of distinguishing between the two different processes of evolution, namely the random, which leads to the emergence of hereditary variation, and the non-random, i.e. natural selection, which leads to adaptation. The importance of this has been pointed out by Bishop and Anderson (1990). This gives us points 2. and 3. of the theory.

2. Instruction about the theory of evolution is divided into two processes – origin of hereditary variation and natural selection.

3. It is stressed that only the process first mentioned is random and that the second is of necessity a consequence of the variation meeting the environment.
Variation in hereditary characteristics. A number of studies have shown that pupils and students tend to believe that all individuals within species and populations are the same. They have a 'typological view' (Greene, 1990; Halldén, 1988; Pedersen & Halldén, 1994; Rudolph & Stewart, 1998). In a minor Swedish study, questions were asked about, among other things, '100 healthy young small herrings in the Baltic' and '100 healthy dog daisies in a meadow', which were selected at random. The students, about 80 from the 9th form at comprehensive school and various programmes at the upper secondary school, were asked if there were any differences between the organisms within the two groups. They had to explain their answers. The vast majority were of the opinion that there was variation in characteristics, but only about 15 % pointed out that this was due to genetic differences. A somewhat greater proportion, about 30 %, explained the variation by differences in the environment. The remainder, about 40 %, noted variation, but gave no explanation of how it had arisen (Landström, 1995, Zetterqvist, 1995).

International studies, e.g. Bishop and Anderson (1990), Bizzo (1994) and Brumby (1981), show that pupils and students believe that the environment is the main cause of the emergence of variation. In a study by Anderson, Fisher and Norman (2002), two multiple-choice questions were set about the origin of variation. Before receiving instruction, 66 % and 85 % of the students, respectively, (n=206), selected alternatives attributing variation to need, will or the environment. Responses of this type indicate that pupils and students think that changes in nature have a definite cause, for which reason it can be assumed that they find randomness difficult to accept.

A number of authors assert that intra-species variation is a prerequisite for evolution, and that the pupils need help in realising this (e.g. Bishop & Anderson, 1990; Smith, Siegel & McInerny, 1995). Unfortunately, there are signs that Swedish biology teachers at the upper level of the comprehensive school do not focus on this variation. When Zetterqvist (2003) interviewed 26 experienced biology teachers, there were two who spontaneously mentioned existing intra-species variation when they described their lessons on evolution. In answer to a direct question, the majority said that they take up intra-species variation. Of these, there were six who connected the variation with natural selection. The teachers knew beforehand that the interviews would deal with how they taught evolution and had been asked to think about how they usually planned and carried out their lessons.

A positive experience has been reported by Wallin (2004). She notes, as did Bishop and Anderson (1990), that if the students have to explain an evolutionary change, e.g. why cheetahs have become faster and faster runners, they often describe a process in which all individuals in the species adapt themselves to the environment through gradual changes. The driving force in this process is that the species needs new characteristics. The question posed tends, in other words, to trigger everyday conceptions. If, on the other hand, the variation in a population is explicitly described in a task, the students are more inclined to discuss differences
in the chances of survival, i.e. they start reasoning according to the theory of evolution by natural selection.

These studies and analyses lead to the following point in our theory:

4. Existing variation in populations is discussed. Genetics is introduced to get an idea of how differences and similarities come into existence. Knowledge about the existing variation in hereditary characteristics is regarded as a necessary platform for proceeding to natural selection, thereby building up an alternative to ideas of evolution caused by need, effort, will, etc.

Survival, reproduction and adaptation. One expression connected with discussions on evolution is 'survival of the fittest'. It is commonly translated into the Swedish equivalent of 'survival of the strongest', which unfortunately misses the point of 'fittest', namely, relative reproductive success. Anderson et al. (2002) tested students' perception of 'fitness' in two multiple-choice problems with different contexts. It was shown that 44 % and 61 % chose alternatives that did not link fitness with reproductive success but with large body size and strength, frequent mating, long life, or success in competing for food.

Few articles contain discussion about differences in reproductive success. Ferrari and Chi (1998) show that many students do not reason about such things but explain evolutionary changes by a new type of individual being born and forming a new species. Bishop and Anderson (1990) refer briefly to the students not discussing differences in reproductive success. The authors deal with fitness and difficulties in understanding the concept, discussing it as a terminology problem. Sinclair, Pendarvis and Baldwin (1997) tested 218 students in pre- and post-tests. In the latter, two-thirds chose other multiple-choice alternatives than the most scientific ones regarding the meaning of 'survival of the fittest'. They preferred alternatives referring to need, health and strength. Jensen and Finley (1995) found, however, that the students learnt the scientific meaning of fitness without much difficulty.

Experience from our own experiments shows that students see differences in survival as a relatively simple and more or less self-evident result of existing variation (Wallin, 2004). As mentioned above, this was apparent in problems where the existing variation was stated explicitly. On the other hand, some students do not realise the decisive role of reproduction in evolutionary development, i.e. that survival that does not result in a relatively larger proportion of offspring in the next generation is, evolution-wise, of no consequence.

Many pupils and students believe that adaptation is the driving force in the process of evolution. They see evolutionary development as a process in which the characteristics gradually develop in all individuals in a population or species (Bishop & Anderson, 1990; Brumby, 1984; Deadman & Kelly, 1978; Halldén, 1988). This is also common after instruction, (e.g. Bizzo, 1994; Halldén, 1988; Sinclair et al., 1997). Bizzo (1994) found, in an interview survey, that only 9 % of the pupils used a population-based explanation for evolutionary adaptation, i.e.
understood adaptation as a change in the proportions of characteristics or genes in the population.

That adaptation is a difficult concept to learn when being taught the theory of evolution by natural selection has been documented for many different languages (Baalmann, Frerichs & Illner, 1998; Bizzo, 1994; Brumby, 1981; Engel Clough & Wood-Robinson, 1985a; Halldén, 1988; Jensen & Finley, 1995; Jungwirth, 1975; Thomas, 2000). One reason may be that this term is used for both everyday and scientific concepts (Brumby 1981). Even within the science of biology, the term is used with different meanings. We therefore think that it might be an advantage, at least by way of introduction, to avoid the word adaptation and to introduce accumulation instead as a term for the change in the proportion of characteristics or genes in the population. Not until the pupils have understood the meaning of accumulation is it appropriate to have a discussion about the evolutionary concept 'to adapt'. It is useful to include other meanings of adapt here, both biological and other.

The discussion above on reproduction, accumulation and adaptation contributes to the theory as follows:

5. Natural selection is divided into two parts:
   • differential survival rate
   • differential reproductive rate

6. It is made clear that differences in survival are not enough to explain evolutionary changes. The crucial factor is differences in reproductive success.

7. Accumulation is introduced as a term for the increasing proportion of individuals with a certain hereditary characteristic due to natural selection. After that the evolutionary meaning of adaptation is discussed.

Levels of organization. The evolution of life is explained in biology at many different levels of organization: DNA/gene/chromosome, individual, population, species and ecosystem. For example, the result of natural selection is discussed at the population level, while the evolutionary discussion on heredity is often held at the individual level, but also at the genetic or population level.

Alternating unconsciously between levels of organization may confuse the learner. Ferrari and Chi (1998) write that one factor contributing to difficulty in understanding natural selection may simply be uncertainty about different levels of organization. Halldén (1988) finds in his study that when the pupils are asked to describe the formation of species, they argue at two different levels, species and individual, without clearly distinguishing between them. The importance of explaining to pupils and students at what level of organization the teaching content is has been demonstrated by Knippels, Waarlo and Boersma (2001) and Knippels (2002). They talk about 'the yo-yo learning and teaching strategy', i.e. moving up and down between the levels of organization.
We conclude from this that the concept of level of organization should be introduced and used, that is to say, different levels and how they are related. This provides the final point in the content-specific part of our theory:

8. The various levels of organization that are used when discussing evolution are made explicit.

**Aspects concerning the nature of science**

*Evolution and religious belief.* The theory of evolution and religious belief in the creation can be difficult to reconcile (Dagher & BouJaoude, 1997). Different ways that pupils use to solve this conflict are described in the literature (Demastes, Good & Pbles, 1995). One example is to accept the scientific description of evolution but to imagine that it was God that started it all off. Another is to keep science and religion separate. The authors conclude that it is possible to have a scientific understanding of the theory of evolution and at the same time a religious faith. Downie and Barron (2000) have studied to what extent biology and medical students accept the theory of evolution. Among those who accept, a good half have a religious faith. The corresponding proportion for those who do not accept the theory is nine out of ten.

There is no consensus in the literature on how teaching about evolution can be undertaken so that students' religious beliefs do not block biological understanding. The most usual standpoint, which has some empirical support (Sinclair et al., 1997), is to discuss the nature of science and the differences between science and other areas of man's conceptual and experiential world (Smith, 1994).

We conclude from this and other studies that the difference between a scientific theory and religious faith needs to be treated in the lessons, and that it should be done with respect for different ways of interpreting and giving meaning to our lives and the world around us. It is, however, not a question of presenting the theory of evolution as something that is neither better nor worse than other ways of explaining the origin and evolution of life. Asimov (1981) points out that: '... no theory is better founded, more closely examined, more critically argued and more thoroughly accepted, than the theory of evolution.'

The studies referred to and our own experience of teaching lead us to the following three aspects concerning the nature of science:

Paying attention to the following aspects (1 - 4) in teaching promotes learning with understanding:

1. When the teaching content is a scientific theory, its character is made explicit (hypothetical in nature, can be used to explain and predict, can be tested by experiments and by observations, cannot be verified to the extent of being absolutely true, gives a consistent understanding of many phenomena and so on).

2. The differences between a scientific theory and faith are discussed. Their own way of understanding the world is respected.
The theoretical integration. When the teaching was planned, the parties involved were agreed that the theory of evolution by natural selection would be the main thread. The pupils would use the theory again and again to understand and explain various phenomena, and in so doing discover that a theory integrates many different observations. Over half the pupils made spontaneous comments on this in their diaries, e.g.:

Now it's starting to dawn on me a little in the evolution theories. Maybe because we (generally) do similar things every lesson. And I think that's good. For then it might not be just surface learning but hopefully it will stick. Everything is much easier and more fun if you understand and know things. (Wallin, 2004, p. 241.)

In another teaching experiment a sequence of lessons in geometrical optics for forms 8 and 9 of comprehensive school was tried out. A main theme was the development and use of a qualitative theory (Andersson & Bach, 2005). Interviews with seven trial teachers showed that some had stressed the theory of geometrical optics as the unifying thread running through the sequence and the importance of using the theory for problem solving. Others, however, did not mention the theory at all, which might be an indication that it was not central to their thinking about teaching geometrical optics. The teachers interviewed used the word theory or theoretical with a variety of meanings. Sometimes it signified something abstract, as opposed to concrete. In some contexts the word theoretical meant that something is difficult. Another example is that a student's guess about the outcome of an experiment was called 'the student's theory.' Andersson's and Bach's conclusion from this teaching experiment was that the importance of theoretical integration needed to be explained better in the teachers' guide.

These results and experiences induced us to add the following aspects:

3. The pupils are offered many opportunities to use the theory as an intellectual tool.

4. The teaching is planned and carried out so that the theory stands out as the main unifying thread.

The possibilities to take aspects three and four into consideration are rich since courses in biology offer many contexts for applying the theory of evolution by natural selection. Examples are family trees, biodiversity, sexual selection, co-evolution, formation of species and ethology.

General aspects

The teacher as a bearer of culture. It was mentioned earlier that one consequence of the constructivist way of looking at learning and knowing is the insight that 'science consists of ideas created by human beings' (see the section General theoretical platforms). This means that the pupils cannot discover concepts and theories by observing and experimenting. They are therefore referred to media and persons with scientific knowledge to learn e.g. physics, chemistry, and biology. We see the teacher as the main figure in this connection. It is he/she who is the
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bearer of the scientific knowledge. Without the teacher's introduction of concepts and systematic planning of situations for the use of concepts, the chance of long term retention is rather slight.

A similar view is represented by Viennot and Rainsong (1999). They are critical of 'discovery learning' and argue that science cannot be understood from or emerge out of discussions between pupils if they are just provided with appropriate problems. Amongst other things, lectures and introductions by the teacher are required. They see the teacher as the one who plays the decisive role in the teaching process.

Not all teachers see their role in this way. In the experiment in geometric optics referred to above, it was observed that the trial teachers interpreted the written guide in different ways. Some understood it to suggest that students should make investigations and think for themselves, with the teacher as an unobtrusive observer. The students of these teachers tended to achieve poorer results than those who played a more active role, despite more time spent on the sequence.

These results and this experience give us the first point in the general part of our theory:

Paying attention to the following aspects (1 - 7) promotes learning with understanding:

1. The teacher looks upon him-/herself as an active representative of the scientific culture, who introduces concepts, gives scientific explanations, and arranges situations for applications of these concepts and so on.

Alternative ideas. We think that the teacher should know and be aware of the alternative ideas described in the literature in order to recognize and deal with them in a positive way during lessons. See e.g. Driver, Squires, Rushworth and Wood-Robinson (1994) for a review of relevant literature. The teacher should also be prepared for new alternative ideas that may turn up. It is probable that a comparison of scientific and alternative ideas and a class discussion on their explanatory power will contribute to improved understanding of science. This point of view is put forward by, e.g. Marton and Booth (2000).

When it is a question of biological evolution, pupils and students tend to conceive it as a process in which all individuals of a species adapt themselves to the environment through gradual changes. The driving force in this process is that the species needs new characteristics. 'Organisms realize – consciously or not – that they have to change under given conditions of living, in order to get adapted.' (Baalman & Kattman, 2001, p. 18). In other words, evolution is understood as need-driven, goal-directed process. This way of reasoning is usually called teleological or finalistic, i.e. evolution has a purpose or a goal. Perhaps this type of explanation goes back to human experience that development is achieved when you try to satisfy needs by heading for stated goals. The explanations can therefore also be regarded as anthropomorphistic.
Other alternative ideas are that evolutionary changes take place because characteristics are used or not used, (e.g. Bishop & Anderson, 1990; Brumby, 1984; Ferrari & Chi, 1998; Settlage, 1994), or when characteristics acquired during a lifetime are inherited, (e.g. Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985b; Kargbo, Hobbs & Erickson, 1980; Ramorogo & Wood-Robinson, 1995; Thomas, 2000; Wood-Robinson, 1994).

Summing up, we get the following two points concerning alternative ideas:

2. The teacher is well acquainted with common alternative ideas of the teaching content and is aware of these during teaching. He/she is attentive to and interested in the pupils' ideas, both those already known through the literature and new ones.

3. The teacher creates a permissive classroom climate in which the pupils can share and discuss their ideas and reflections in a positive way.

To these three general aspects we have added the following:

4. A fair amount of time is used for discussing and solving problems/problems involving the pupils in having to apply the teaching content in different situations.

5. Deep learning is encouraged, i.e. the pupil is stimulated to
   • 'twist and turn' the new knowledge in his/her head (transformation instead of memorisation)
   • ask questions and suggest ideas
   • connect new knowledge with existing knowledge
   • use knowledge as a tool for seeing the world around him/her with new eyes
   • discuss what is new with classmates and others
   • accept challenges (e.g. in the form of set problems)

6. Formative evaluation is used in various ways by both teachers and pupils with the purpose of improving teaching and learning.

7. The teacher does not assume that the student is motivated but acts to create interest and motivation.

Both aspects 4 and 5 may be seen as a development of the first of Ogborn's four points, which are described in the section 'General theoretical platforms'.

Aspect 6 is supported by relatively comprehensive documentation showing that, if formative evaluation is improved and is done more deliberately and systematically, teaching and learning can also be improved (Black & Wiliam, 1998).

We believe that the seven general aspects listed are rather well known by researchers in science education. However, in our experience they are not so well understood by teachers at school. We have listed them to make the presentation of our theory coherent and hopefully usable in practice.
Discussion

Methodological issues

Lasting understanding is seen as a criterion of validity. It is evident that our content-oriented theory is fairly complex. It consists of three parts, and these in their turn of a number of aspects. One interesting question is how such a theory can be tested. A first requirement of validity, we think, is that teaching should lead to lasting understanding. What about our own attempts in this respect? In our three experiments, teaching was carried out largely according to the theory's different points. The group of researchers and teachers did not, in fact, have any explicitly formulated theory during the first two experiments, but when minutes from project meetings, detailed lesson plans and field notes were studied, most of the different points of the theory could be identified, but not the one referring to accumulation and adaptation, which did not appear until the third experiment.

After comparing the results of a pre-test and a delayed post-test about one year after completed instruction, we claim that the teaching sequence in question leads to lasting understanding for a large proportion of the pupils. The pre-test contained seven written problems. Most of these involved answering in your own words. The same problems were set in the delayed post-test, and one more was added. Altogether 79 pupils from the three experiments completed both the pre- and post-test. Scientific concepts dominated the answers of 19% of the pupils in the pre-test. The proportion rose to 73% in the post-test. The proportion of pupils who consistently demonstrated scientific concepts in the pre-test was 6%. In the post-test this pupil category accounted for 43%.

One of the problems was worded as follows:

Cheetahs are able to run fast, around 100 km/h, when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could only run 30 km/h.¹

It was constructed by Bishop and Anderson (1990) and has been used in many studies. Of our 79 pupils, 20% had only scientific explanations in the pre-test. In the delayed post-test the proportion is 75%. It is problematic to compare these results with those from other studies as a number of variables are not controlled, e.g. age of pupils, teaching time and content of lessons. Bearing this in mind, it is noted that, in general, the improvement in results reported has not matched ours (Bishop & Anderson, 1990; Bizzo, 1994, Demastes, Settlage & Good, 1995). Good long-term retention was achieved in a study by Jiménez-Aleixandre (1992). The pupils were 14 years of age, and the teaching comprised 8 'sessions' in the space of two weeks. On average, they gave scientific answers to 60% of the test problems after one year.

Comparison with teaching praxis. Another question is whether a teaching sequence designed on the basis of a content-oriented theory really constitutes a substantial improvement in learning compared with the 'prevailing teaching praxis', a concept whose meaning is not self-evident but can be defined to a
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certain extent by analysing popular text-books. One way to answer this question is to acquire a control group that is taught conventionally. This involves many practical difficulties, but they are not insurmountable. Our experience is, however, that for a given topic the designed teaching takes longer than the conventional lessons, i.e., the variable 'teaching time' is not controlled. That more time is required for the former is not strange. More recent science education research results often show previously unknown difficulties of different types that the teacher in general is not aware of and, consequently, in contrast to the design group, does not take up in the lessons.

An interesting result from the sequence about geometrical optics mentioned above (Andersson & Bach, 2005) is that one teacher who taught the sequence three times in succession with different groups achieved better and better results. Dialogues during classroom visits showed that he understood the intentions and content of the teaching sequence better and better. This is an indication of the importance of the teacher in the achievement of good results and a reminder that one should not automatically make drastic changes in a teaching sequence that has perhaps not produced such good results the first time it was tested.

Speaking about the sequence in geometrical optics, it was possible to some extent to use the same test problems as in the national assessment (Andersson, Bach, & Zetterqvist, 1997). It was then evident that the pupils taught according to the designed sequence in many respects answer markedly better than the national sample (Bach 2001; Andersson & Bach, 2005). This points to the possibility of integrating national assessments into research projects that are aimed at improving school teaching.

What significance do different aspects of the theory have? Good learning gains confirm the content-oriented theory on a general level. But what is the significance of the content-specific, general, and nature of science aspects, respectively? And, on an even more detailed level, what is the significance of the various aspects? In principle, this question may be answered by comparing two teaching sequences that only differ with respect to one of several factors. However, the more the studied variable is refined, the weaker is its effect likely to be compared with the total teaching environment, which may render any positive differences insignificant.

Another possibility of getting at the critical aspects of learning is to follow individual students throughout the teaching sequence. The important thing is how the student interacts with different influential factors. One difficulty is that this influence may have a delayed effect. Who has not woken up in the morning and suddenly understood something that seemed impossible to grasp the day before?

Theory-related evaluation. So far we have not carried out a teaching sequence in our group with a content-oriented theory that has been clearly formulated from the start. If the teachers and researchers involved have formulated such a theory, it can direct attention to events that confirm or refute the theory, and they can record
these. An example of such an observation was given earlier (see Theoretical integration) according to which about half the pupils state spontaneously that aspects 4 and 5 about the nature of science are experienced positively and help them to learn with retention.

Another example is an interactive internet problem using a database, which the pupils set about trying to solve immediately after being introduced to the theory of evolution by natural selection (Wallin & Andersson, 2004). It is about how a reindeer population develops over several generations, focusing on the length of legs. They are given the proportions of short, medium and long legged reindeer to start with. It turns out that 16 of 18 pupils take up evolution arguments at once. This we interpret as a confirmation of aspect 4 of the content-specific part of the theory.

One possibility that has not been researched is simply to ask the pupils about different aspects of the theory, e.g. about how they experience them.

**Two ways of formulating content-oriented theories**

The only examples of content-oriented theories that have been dealt with thoroughly and that we know, and consequently can compare with our own theory, are those described by Lijnse and Klaassen (2004). To obtain a fairly controlled comparison, we have chosen one of their theories that refers to a particle model for solid, liquid and gas states. As in our case with evolution by natural selection, it is a question of introducing and applying a scientific theory. One important part of the Dutch researchers’ theoretical work is to write a scenario:

> We develop *teaching-learning materials* for teachers and students. However, we do not just write them rather intuitively as textbook writers usually do. In fact, we develop them in parallel with a *scenario*. This scenario *predicts* and theoretically *justifies* in detail the teaching-learning *process* as it is *expected* to take place and *why* it is expected to happen in that way. This relates in particular to the interaction of teaching and learning activities. (p. 540)

The scenario is regarded as a preliminary sketch of a domain-specific theory. After the scenario has been subjected to a number of tests and revisions, the most important steps for a ‘didactical structure’ are abstracted. This structure consists of a flow chart describing a teaching route with respect to the current content (physics knowledge) and the nature of the content (nature of physics). Motivation aspects are integrated into the flow chart. The authors take great care all the time that the pupils understand the point of what they are doing, i.e. they try and create content-related motivation in the pupils.

There is actually no theoretical statement connected with the didactical structure. One such statement could perhaps be worded as follows: If the teaching is done according to the flow chart, the probability of the pupils attaining a good understanding, or better understanding than prevailing teaching praxis, increases.

When comparing the Dutch approach and our own, we note the following:
Content-specific motivation is integrated into the Dutch theory, while it is expressed in general terms in ours. We think that this idea of content-specific motivation is a strength of the Dutch approach.

The parts 'scientific content' and 'the nature of science' are coordinated in the Dutch theory, while in ours they are separate. An advantage of the Dutch approach may be the very coordination into a suitable sequence. A teacher might, however, feel that our way is more flexible, as he/she does not need to feel bound to follow a given sequence.

We think that our content-specific aspects are more explicit, i.e. closer to the teaching content, than the Dutch ones, which are more general in character. Two examples are 'involving students in a disciplined modelling process, that leads to a further development of the model with an increased plausibility' and 'that is explored by a further development of the gas model and its applications to the behaviour of liquids and solids as well'. We therefore believe that our theory may be easier for an interested teacher to understand and apply, but we have no empirical evidence to report in this respect.

Our theory contains general aspects, which are rooted in a social constructivist view of learning and general pedagogical wisdom. There is no equivalent of this in the Dutch theory.

**Presenting research results for further knowledge-building**

We believe that it is of vital importance to document the results of design research in such a way as to stimulate continued knowledge-building among teachers in school. The question is how this may be achieved. One possibility is to place the emphasis on discussing motives for teaching the content in question, presenting analyses of its nature, describing its historical development, reporting relevant research results, and stating suitable goals for teaching. Another possibility is to concentrate on describing a number of tested lessons and supplying texts for pupils and other resources. In the former case, the teacher has to do a lot of work to transform the knowledge base into concrete teaching. In the latter case, the teacher receives a good recipe in itself for a number of lessons but has no explanation of why lessons and resources have been designed in that particular way. This may reduce his/her chance of adapting the teaching to his/her own pupils and of dealing with unexpected events. It appears, in other words, that we are faced with a problem of balance, as has been pointed out by Fishman and Krajcik (2003).

Cobb (2000) throws light on this problem when reporting his experiences of classroom experiments. He writes:

... we have found it counterproductive to plan the details of specific instructional activities more than a day or two in advance. This emphasis on an ongoing process of experimentation is compatible with M. Simon's (1995) observation that 'the only thing that is predictable in teaching is that classroom activities will not go as predicted'. (p. 320)
This may be seen as an argument for emphasising detailed background information. It may be interpreted as an argument against describing a sequence of lessons.

Lijnse and Klaasen (2004) also elucidate the problem. They write:

... although a best way of teaching a topic may indeed be an illusion, we do think that some ways are better than others; and therefore that it is worthwhile to search for evidence of how and why that is the case and for means that enable to express and discuss the didactical quality of such teaching sequences and situations. (p. 538)

Our own approach is to be rather exhaustive with regard to both background information and describing a number of tested lessons showing how available didactical knowledge can be transformed into concrete teaching. We therefore think that the following should be reported:

- Discussion about why the given area should taught at school.
- Analysis of the scientific content (conceptual structure, relations to other areas, social significance, etc.)
- Explanation of subject matter if required, which may include a review of its historical development.
- Report and analysis of research results about pupils’ conceptions and opportunities for understanding, as well as results of any attempts at teaching the area.
- Suggestions for goals in relation to the pupil’s starting-point.
- Discussion about conditions that promote learning the given area with understanding. These conditions may be expressed in the form of a hypothetical content-oriented theory.
- Suggestions for a number of lessons that exemplify how the content-oriented theory may be put into practice.
- Report of various results (what the pupils have learnt and what they felt about the teaching, the experience of the trial teachers, etc.)

The teaching can also be supported by certain resources that have been produced during the design work, e.g. texts for pupils and problem collections. We call this type of report a ‘teacher’s guide for further knowledge-building’. We have published one such guide for the teaching of geometric optics (Andersson & Bach, 2003).3

Our experience of how teachers tend to read this type of document is that they study the suggestions for lessons first. If they find these interesting, realistic and thoroughly prepared, they accept the document. Perhaps this is basically a question of trust. As researchers, we have to 'win' this on the teachers' own ground, i.e. show that we not only have theories and analyses but also the capacity to apply this knowledge in teaching.

A content-oriented theory like ours can be useful when it is a question of achieving the required balance between background information and descriptions of lessons, thereby contributing to a flexible use of the teacher’s guide. The theory with its three parts is the point of departure and the lesson sequence described just one of a number of possible applications. One teacher will perhaps stick to the
theory and design his own application. Another will use some of the lesson suggestions and resources. Yet another will decide to test the whole sequence described. If the experience of this is negative, he/she can return to the theory and perhaps redesign the lessons or produce new ones.

A fair number of good teaching sequences in the science area have been developed in Europe. Unfortunately, the results of this design research can hardly be said to be easily accessible to interested teachers in different countries, among other things because the teacher's guides and pupil material are only available in the language of each country. It is therefore justified to start considering what would be entailed in building up a European database to access the collection of European knowledge in the area in an appropriate way and in a suitable language for interested teachers in different countries, and naturally for researchers as well.

Reflections in a wider context

Researchers who work with science education have long sought and used different theoretical platforms with the purpose of obtaining a suitable scientific foundation on which to stand. During the 1970s the works of Piaget were important, not least his descriptions of the reasoning patterns pupils could use at different ages. During the 1980s various constructivist theories dominated, which among other things led to comprehensive surveys of pupils' conceptions of different scientific phenomena. During the 1990s the study of communication processes came more and more into fashion, based on socio-cultural theories. At the beginning of the millennium it is noted that several theoretical platforms are being used in an attempt to understand the complex teaching and learning processes that take place in our schools. Duit (2000) speaks of 'multi-perspective theoretical orientation'.

There is no doubt that these different efforts have increased our understanding of teaching and learning science. A common feature is that the theoretical approaches are derived from other areas of knowledge than science education. In this article we have tried to clarify a supplementary option, namely that science education research creates its own theories. We hope that our examples with conditions that promote learning about the theory of evolution by natural selection, as well as the cited work of Lijnse (2000), Lijnse and Klaasen (2004) and Andersson and Bach (2005) show that this can be done. If work such as this is successful, the research into science education as an independent academic specialization will gain ground. In our opinion, there is a pronounced risk that our academic identity will be lost if our research is looked upon as applied cognitive psychology, applied socio-cultural theory or whatever it might be.

NOTES

1. The formulation of this problem may communicate a typological view of cheetahs. One gains the impression that all cheetahs can run 100 km/h, i.e. that no variation exists as regards the characteristic 'run fast'. This way of expressing oneself about species is perhaps common among biologists and biology teachers, in which case it calls for didactical reflection.
2. The address for a version of the problem in English is http://na-serv.did.gu.se/reindeer/

3. The guide, which is in Swedish, may be downloaded from: http://naserv.did.gu.se/lightguide.pdf (211 pages, 8.5 MB).
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