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The theory of evolution in the classroom
Towards a domain specific theory for teaching biological evolution

ENGLISH SUMMARY

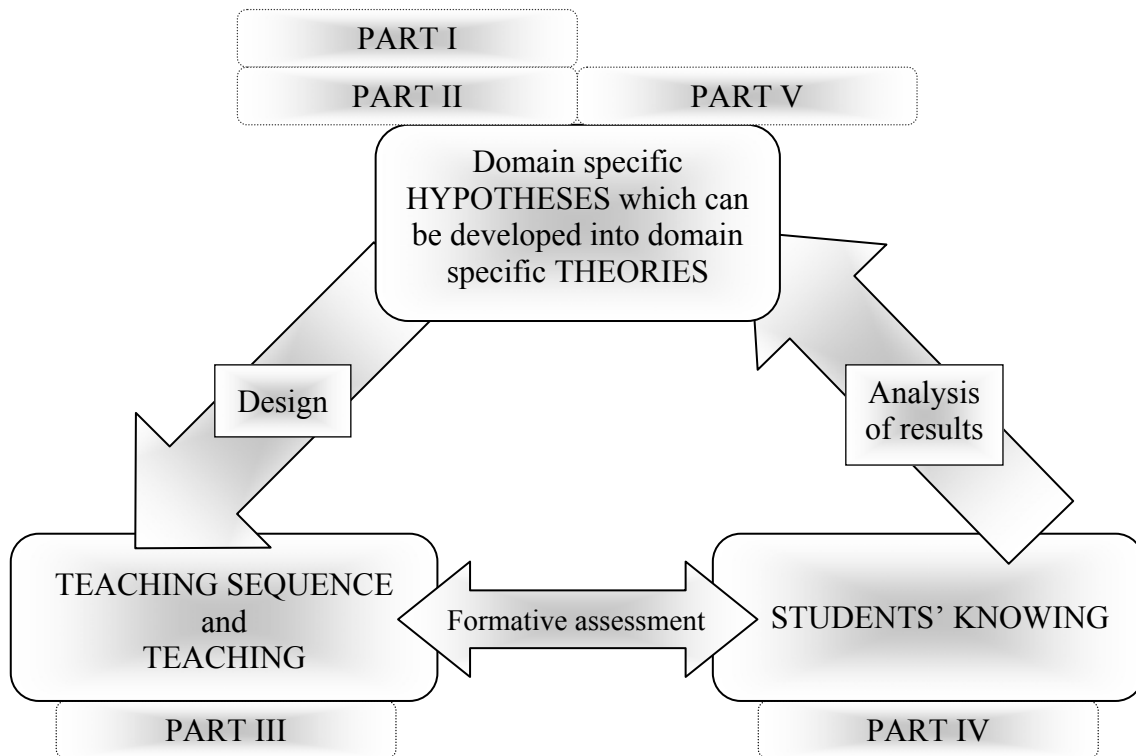# Abstract

The overall purpose of this thesis is to study how upper secondary school students (grade 10-12) develop an understanding of evolutionary biology as a result of teaching. Taking students' preconceptions as the starting point a teaching sequence is designed with the aim that students shall learn the theory of evolution by natural selection in such a way that it becomes an intellectual tool. In other words they shall be able to describe, understand, explain, and partly predict biological phenomena from an evolutionary point of view.

Three different teaching experiments were performed and studied in a cyclic process with design and evaluation of both teaching and students' learning, followed by a new design and so on. The students' knowing was tested before, during, and after teaching by written tests, interviews, small group discussions, and a database-driven Internet problem. Similar results emerge from the analyses of the students' performances in the different data collections: e.g. all students do not accept random processes before teaching, many students use the same alternative ideas, and existing variation is a key idea to understand the theory of evolution, and to reason scientifically. The majority of the students, about 80 %, had alternative ideas about evolution before teaching. They viewed evolution as a gradual process where every member of the population adapts to the environment. They consider adaptation as the driving force that is regulated by, for instance need, strive, or purpose. In the delayed post-test one year after teaching most students, about 75 %, had reached a scientific level. This result can be considered good compared to many other studies reported in the literature.

The students' reasoning in the different tests was carefully analysed having preconceptions, the conceptual structure of the theory of evolution, and the aims of teaching in mind. This gave insights into those learning and teaching demands that constitutes challenges to students as well as to teachers, when beginning to learn, or to teach evolutionary biology. The combined results from these analyses of the three experiments are summarized in a domain specific hypothesis for teaching. It consists of three different aspects: content specific aspects, which are unique for every field of science, aspects concerning the nature of science, and general aspects. This hypothesis can be tested in new design experiments, and if it will withstand future tests it can be developed into a domain specific theory for teaching evolutionary biology.

ENGLISH SUMMARY

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INTRODUCTION

The overall purpose of this thesis is to study how upper secondary school students (grade 10-12) develop an understanding of evolutionary biology as a result of teaching. Taking students' preconceptions as the starting point a teaching sequence is designed with the aim that students shall learn the theory of evolution by natural selection in such a way that it becomes an intellectual tool. In other words they shall be able to describe, understand, explain, and partly predict biological phenomena from an evolutionary point of view.

The students' reasoning in different tests was carefully analysed having preconceptions, the conceptual structure of the theory of evolution, and the aims of teaching in mind. This gave insights into those learning and teaching demands that constitutes challenges to students as well as to teachers, when beginning to learn, or to teach evolutionary biology. The combined results from these analyses are summarized in a domain specific hypothesis for teaching.

PART I: THEORETICAL BACKGROUND

This part starts with a description of the theoretical framework for learning taken in this thesis, followed by a section about different ideas about evolution, both the students' preconceptions about evolutionary phenomena and the scientific idea. It ends up with the topic 'design of teaching sequences in science'.

Theoretical framework

The theoretical framework is constructivist and builds on Piaget's genetic epistemology as presented in Furth (1969). Karmiloff-Smith (1992) worked together with Piaget and claims that later research has shown that human beings are born with even more developed structures for learning than Piaget claimed. Accordingly, before any formal education starts, children have constructed personal understanding about several phenomena in the world. A point of departure for learning is in the individual's genes and this characteristic has developed and adapted in prevailing environments though the history of the species. In the whole, the genes and the environment are prerequisite for the expression of any trait of an individual.

Research on teaching and learning science has, for some decades, been dominated by investigations on students' conceptions, first on the content level and later also on meta-levels, e.g. conceptions of learning and of the

nature of science. The studies on alternative conceptions have to a large extent been focused on individual learning. In this perspective the 'conceptual change model' for learning was developed (Posner, Strike, Hewson & Gertzog, 1982). However, the classical conceptual change model has been criticised for paying too little attention to e.g. social influences and affective and motivational aspects of learning (Pintrich, Marx & Boyle, 1993; Pintrich, 1999; Duit & Treagust, 2003) and for positing conceptual *exchange*, rather than other possibilities (Caravita & Halldén, 1994; Helldén & Solomon, in press). As a response to this criticism there has been a development for merging individual and sociocultural perspectives on science learning and teaching (Strike & Posner, 1992; Hewson, Beeth & Thorley, 1998; Duit & Treagust, 2003). Duit and Treagust address the criticism about conceptual exchange as follows:

> *... It should be remembered that a replaced conception is not forgotten and the learner may wholly or partly reinstate it at a later date.* (p. 676)

> *Most of the evidence from this study indicated that conceptual change which meets the criteria of dissatisfaction, intelligibility, plausibility and fruitfulness is not necessarily an exchange of conceptions for another but rather an increased use of the kind of conception that makes better sense to the student.* (p. 677)

Scientific knowledge consists of abstract ideas that are socially agreed upon. The scientific ideas do not correspond directly to the phenomena as such. Rather, they are concepts, models, and theories that are good enough to describe, understand, explain, and make predictions about these phenomena (Millar, 1989; Driver, Asoko, Leach, Mortimer & Scott, 1994). These concepts, models, and theories can sometimes seem simple, but have been constructed through hard intellectual work. However, looking at science as socially constructed and agreed doesn't imply relativism. Scientific knowledge is restricted by the characteristics of the world and has an empirical base. Lijnse (2000) expresses this in a wise manner:

> *...In spite of all the conceptual relativism that is so fashionable nowadays, I still look at physics as a body of largely reliable knowledge with which one can successfully explain and predict, as well as develop new technology. Above all it is a field in which we now know considerably more than, say, 30 years ago – that is, in which real progress seems to be possible.* (p. 309)

Ideas about evolution

I will focus on different ideas about evolution, the students' preconceptions and the scientific concepts. The gap between preconceptions and scientific ideas constitutes both learning and teaching demands, which is a challenge to students as well as teachers, when beginning to learn, or to teach, a specific content.

Students' alternative ideas

Children have ideas about evolution before any formal education (Deadman & Kelly, 1978; Engel Clough & Wood-Robinson, 1985a). These ideas are not consistent, in most cases, with biological knowledge and I call them 'alternative'. Several studies have shown that students' understandings have not improved much even after relevant teaching (e.g. Halldén, 1988; Bishop & Anderson, 1990; Bizzo, 1994; Demastres, Settlage & Good, 1995). Bishop and Anderson noticed that most students have a conception of evolution as a process in which all individuals in a species adapt to the environment through gradual changes.

Common among alternative ideas is the opinion that the process of evolution is need-driven (e.g. Engel Clough & Wood-Robinson, 1985a; Bishop & Anderson, 1990; Settlage, 1994; Demastes, Good & Peebles, 1995). If one does not notice intraspecific variation the students often use needs in their reasoning (Greene, 1990). Several students use adaptation as the driving force in the process of evolution (e.g. Brumby, 1984; Halldén, 1988; Bishop & Anderson, 1990; Settlage, 1994; Baalmann & Kattman, 2001). Other alternative ideas are that evolutionary changes occur as a result of the use or non-use of an organ, a structure or whatever (e.g. Brumby, 1984; Bishop & Anderson, 1990; Settlage, 1994; Ferrari & Chi, 1998), or the inheritance of acquired characteristics (e.g. Kargbo, Hobbs & Erickson, 1980; Engel Clough & Wood-Robinson, 1985b; Bishop & Anderson, 1990; Wood-Robinson, 1994; Ramorogo & Wood-Robinson, 1995; Thomas, 2000).

Scientific ideas

Evolutionary theory is nowadays generally considered to be a cornerstone in the science of biology, and it provides a unifying framework for biological knowledge. This makes the theory of evolution necessary for a sound understanding of biology and implies that it should be a central part of biology education. As several studies have shown, many students have problems with understanding it. A major reason for these problems might be that its principles may seem counter-intuitive; both in relation to the students' own experiences of biological phenomena and to the everyday language used to explain such phenomena. Another reason might be that this theory explains the development of life itself and interacts with people's worldview.

The theory of evolution can rather easily be described by using three concepts: existing variation, heritage, and natural selection. If the individuals in a population show variation in some characteristics, which are geneti-

cally determined and hereditary, some individuals will be more successful in surviving and reproducing than others. This will result in changes in the composition of the population. The process is called *natural selection*. If the processes result in changes, which are consistent over time, then evolution will be the consequence.

The learning and teaching demands

Most students have alternative ideas about evolution, whether they have been taught the subject or not. The difference between the students' alternative ideas, and scientific ideas, forms the basis for the challenge of teaching. This is one of the main focuses of my interest. The students and the teacher have a common challenge for learning and teaching. Leach and Scott (2002) describe this as 'learning demand':

> *The concept of 'learning demand' offers a way of appraising the differences between the social language of school science and the everyday social language which learners brings to the classroom. The purpose of identifying learning demand is to bring into shaper focus the intellectual challenges facing learners as they address a particular aspect of school science; teaching can be designed to focus on those learning demands.*

I will conclude this thesis with a domain specific hypothesis for teaching evolutionary biology. I suggest that it constitutes one way of meeting the learning and teaching demands.

Design of teaching sequences

The process of designing teaching results in itself in a research-based teaching sequence (e.g. Tiberghien, 1996; Méheut & Psillos, 2004). As such, its usefulness is empirically testable and comparable with, for example, research literature or findings from national and international assessments. The detailed analysis of students' knowing gives another type of results, which may help in generating domain specific hypotheses for teaching.

Today there is growing evidence that the implementation of research-informed teaching will enhance students' learning (Leach & Scott, 2002). Design research has the potential to fill the gap between theoretical research on teaching and learning, and the practice of teaching (e.g. Lijnse, 1995; Hiebert, Gallimore & Stigler, 2002; 'The Design-Based Research Collective', 2003). Research can contribute to filling this gap at three levels (Andersson, Bach, Hagman, Olander & Wallin, 2003):

1. Making general recommendations.
2. Generating domain specific theories.
3. Producing teacher guides, built upon these domain specific theories.

PART II: AIMS AND DATA COLLECTIONS

As mentioned in the introduction, this thesis has two comprehensive aims: to develop a domain specific hypothesis for teaching evolutionary biology, and to design a teaching sequence. In this way, the thesis develops in two directions that many authors have proposed, namely creating general teaching hypotheses and improving the practice of science teaching (Bassey, 1981; Brown, 1992; Lijnse, 1995; Hiebert et al., 2002; 'The Design-Based Research Collective', 2003; Cobb, Confrey, diSessa, Lehrer & Schauble, 2003; Andersson, Bach et al., 2003; Méheut & Psillos, 2004). The following questions are addressed:

- How can a research-based teaching sequence be characterised?
- How can students' knowing about the theory of evolution be characterised before, during, and after teaching, in terms of content of ideas and in consistency of use of ideas?
- How can the development of student's understanding of evolution, as a result of teaching, be characterised?
- How can a domain specific hypothesis for teaching about biological evolution be characterised?

Table 1. An overview of data collections from the three experiments (exp1, exp2 and exp3) and the number of students participating.

Data collection	Exp1	Exp2	Exp3
Before teaching			
Pre-test	43 students	23 students	24 students
Interviews about the origin of variation and about natural selection		12 and 10 students respectively	
The teaching sequence starts			
The teaching is observed	No	Yes	Yes
Interviews about the origin of variation and about natural selection	12 and 35 students respectively	10 and 12 students respectively	
Small-group discussions about natural selection			18 students
Individual database-driven internet problem			18 students
Post-test performed in school (exp1 and exp3) or at home (exp2)	46 students	22 students	18 students
The teaching sequence ends			
Delayed post-test	47 students	20 students	18 students

Data collections

Table 1 gives an overview of the data samples, which form the basis of findings reported in the thesis. The data were collected in three different experiments (exp1, exp2, and exp3). This was done between February 1999 and January 2002. The three experiments were differently designed by taking into account experiences gained during the study. In that way the study can be seen as a cyclic process with design of teaching, evaluation of teaching and students' learning, followed by a new design and so on during three cycles. The experiments were performed in two different upper secondary schools, and with two different teachers. The students were between 17 and 19 years old during the study. The teaching sequence was a part of the obligatory course in biology in the science programme.

PART III: TEACHING SEQUENCE AND TEACHING

In this part I address the question: ' How can a research-based teaching sequence be characterised?'
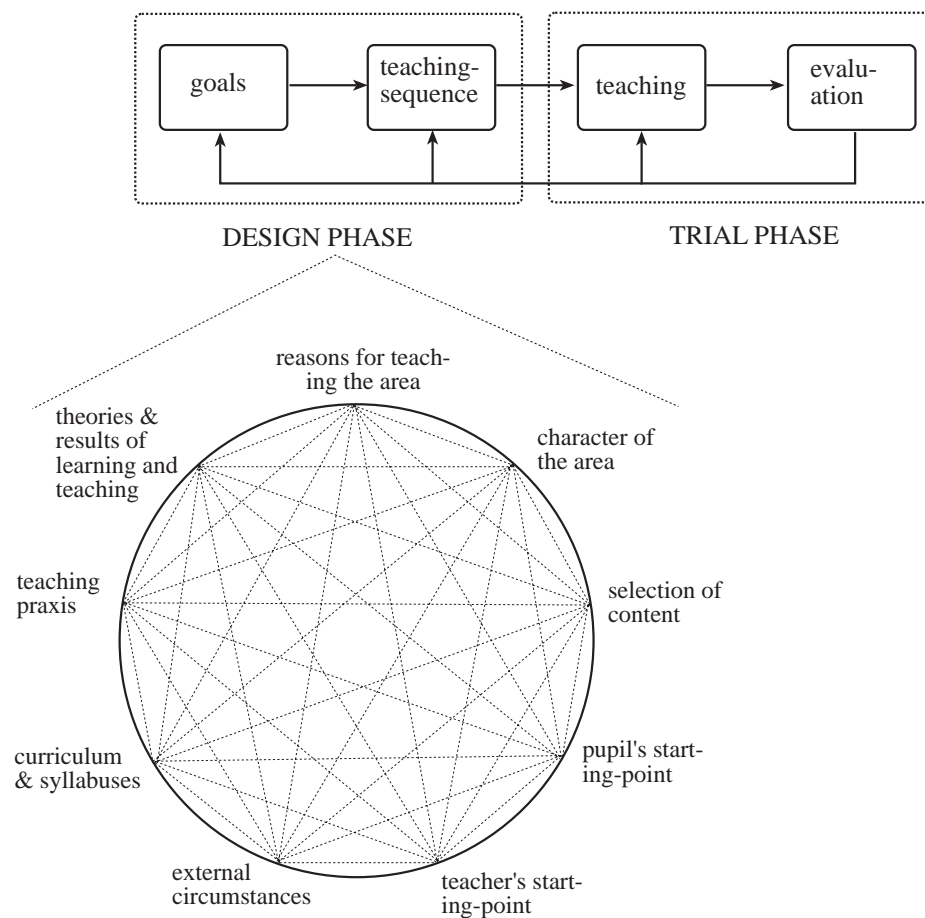

Figure 1. Design of teaching. The different aspects which are taken into consideration and which interact are given at the periphery of the circle.

Figure 1 illustrates the whole process (Andersson, Bach et al, 2003). The overall goal of students' learning was unchanged during the three experiments, and in focus was the theory of evolution. This theory is what the students are expected to learn in a manner that it becomes an intellectual tool, applicable across a range of different contexts.

The design phase gives rise to a teaching sequence (table 2). In our case it consists of nine lessons of variable length, one occasion for a test, one for responses to that test, and finally an evaluation of the whole sequence. All together these nine lessons constitute a cohesive unit taking about 13 hours. The teaching is evaluated in different ways. The experiences of the students and an observer were investigated in conjunction with the result of the students' learning, their knowing about the theory of evolution, and the development of this knowing.

Table 2. Content and duration of lessons.		
Lesson	Short description	Duration (minutes)
1	Historical perspective on ideas about evolution (lecture) Basic genetics; DNA, inheritance and mutations (lecture) Origin of variation (group discussion)	120
2	Time; analogies (lecture) Timeline in the schools corridor (student activity)	80
3	Common descent, speciation, extinction (lecture) Origin of life (group discussion and computer activity) The giraffe's long neck (group discussion)	90
4	Role play with historical texts (student activity) Peppered moth (lecture) Natural selection game (student activity)	80
5	Nature of science: especially belief and science (lecture) Main strands of the theory of evolution (lecture) Chance: Yatzy (student activity) and "the eye" (lecture) Co-evolution (lecture and group discussion)	80
6	Levels of organisation, example: sickle cell anaemia (lecture) Antibiotics resistance (group discussion), Reindeers' legs (computer activity)	90
7	Evidence for evolution (lecture) Fossil reconstruction (student activity)	80
8	Speciation: allopatric and sympatric (lecture) Speciation of salamanders, Ensatina (student activity)	90
9	Significance of animal behaviour for survival and reproductive success: Fitness, animal behaviour and sexual selection (lecture) On which level of organisation does evolution work? (group discussion)	80

The teacher has a central and important role in this teaching sequence. He/she not only has to create a classroom atmosphere that is open and

friendly and invites the students to express and discuss various ideas, but also to introduce and support scientific ideas in the classroom. Special effort was made to show the students that all contributions were taken seriously. Much of the authority to decide what ideas are counted as valid was handed over to the students, who were allowed to decide this for themselves on the basis of the explanatory power of the ideas. All discussions, both in the whole class as well as in groups, had specific aims and structured frames regarding time, number of students and material. The teacher is very important in developing opportunities for students to learn (Viennot & Raison, 1999; Leach & Scott, 2002).

PART IV: STUDENTS' KNOWING

Written tests – pre-test, post-test performed at school or at home and delayed post-test – have been used to study the students' knowing and the development from the pre-test until the delayed post-test made approximately one year after teaching. Further, the students' knowing in biological evolution was investigated through structured individual interviews, structured small group discussions, and through a database-driven Internet problem. Two specific questions were addressed in this part: 'How can students' knowing about the theory of evolution be characterised before, during, and after teaching, in terms of content of ideas and in consistency of use of ideas?' and 'How can the development of student's understanding of evolution, as a result of teaching, be characterised?'.

Categorization of students' reasoning

Students' reasoning was categorized and ranked. Their answers to the open-ended problems were firstly divided into two main groups:

A. Alternative ideas about evolution
V. Scientific ideas about evolution (the Swedish word corresponding to scientific is 'Vetenskaplig')

A. Answers with alternative ideas were classified into categories, based on the students' reasoning:

- vague reasoning about development, evolution,   vague development
  or adaptation
- need-driven evolution   need
- organs which aren't used will disappear   not use
- learned and acquired characters evolve   learning
- other   other

V. Answers with scientific ideas were classified according to the following five components:

- individual variation   'variation'
- differential survival rate   'survival'
- differential reproduction rate   'reproduction'
- genetically determined heritability   'heredity'
- accumulation of changes   'accumulation'

Each of these answers was ranked between 1 and 8. Rank 1 is no answer whatsoever. The ranking is shown in table 3.

Table 3. Ranking of the answers to open-ended problems in the pre-test, post-test and delayed post-test.

Components/ideas	Category	Rank
Variation Survival Reproduction Heredity Accumulation	Scientific IV	8
Variation Survival + additional 2 components	Scientific III	7
Variation Survival + additional 1 component	Scientific II	6
Variation Survival	Scientific I	5
Alternative ideas about evolution + additional component or scientific term	Alternative II	4
Alternative ideas about evolution	Alternative I	3
Don't know/ irrelevant	Don't know/ irrelevant	2
No answer	No answer	1

Examples of results from written tests

Results are presented from a multiple-choice problem and an open-ended problem that were both used in pretest and delayed post-test. A comparison is made between the students' performance in open-ended problems in pre-test, post-test, and delayed post-test. This section will end with results concerning how consistent the students are in using alternative and scientific ideas in pre-test and delayed post-test.

The 'existing variation' problem

This multiple-choice problem about 'existing variation' is included both in the pre-test and the delayed post-test:

> *A number of mosquito populations are today resistant to DDT (a chemical used to kill insects), so that DDT treatment now is less effective than it used to be. Biologists believe that the DDT resistance evolved because:*

1	Individual mosquitoes developed resistance to DDT after being exposed to it.
2	The mosquito populations needed to be resistant to DDT in order to survive.
3	A few mosquitoes were probably resistant to DDT before it was ever used.
4	The mosquito populations became resistant by chance.

In figure 3, students' choices of the multiple alternatives are shown. As no significant[50] differences exist between the experiments, data are pooled. On the other hand, the students' choices differ significantly[51] between the pre-test and the delayed post-test. No significant[52] differences exist between males and females. The numbers of students who choose the scientific alternative 'existing variation' increase from 13 to 46.
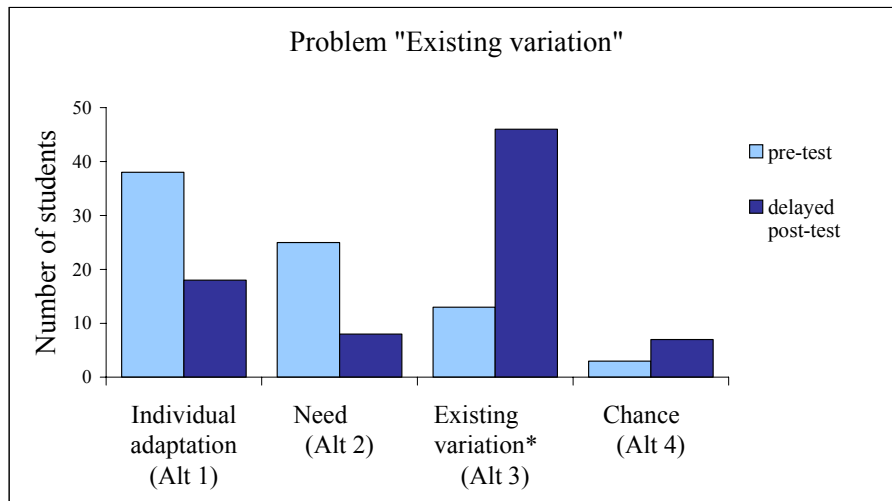

Figure 3. Number of students choosing different alternatives in pre-test and delayed post-test (n=79)

The 'cheetah' problem

This problem is open-ended and is included both in the pre-test and delayed post-test, and has been used in many investigations (Bishop & Anderson, 1990; Bizzo, 1994; Settlage, 1994; Demastes, Settlage et al., 1995; Jensen & Finley, 1995):

> *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?*

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[50] Chi2-test; 2*2 table; pre-test p(exp1 vs exp2)=0,283; p(exp1 vs exp3)=0,735; 2*4 table p(exp2 vs exp3)=0,421; delayed post-test p(exp1 vs exp2)=0,457; 2*2 table p(exp1 vs exp3)=0,592; p(exp2 vs exp3)=0,095
[51] Chi2-test; 2*4 table; p<<0,001**
[52] Chi2-test; 2*4 table; p(pre-test)=0,361; p(delayed post-test)=0,566

The results, from the third experiment (exp3), are shown in table 4. Students with equal results in pre-test and delayed post-test appear on the diagonal. There is one student who has the same rank in both tests. The other students (17 out of 18), whose results are above the diagonal, show a higher rank in the delayed post-test compared to the pre-test. No student ends up below the diagonal.

Table 4. The number of students in the third experiment (exp3) distributed over the different ranks of the 'cheetah' problem in pre-test and delayed post-test (n=18).

Exp3		Pre-test								
	rank	1	2	3	4	5	6	7	8	Σ
Delayed post-test	8			1		2		2		5
	7			5	2		1			8
	6			2						2
	5			1						1
	4									
	3	1		1						2
	2									
	1									
	Σ	1		10	2	2	1	2		18

Open-ended problems

The students got a task, similar to the cheetah problem in the post-test, at the very end of the teaching sequence. A comparison among the three groups' performance on open-ended tasks is shown in figure 4. This is presented as group mean ranks in pre-test, post-test, and delayed post-test. In the pre-test the mean ranks differ significantly[53] between the experiments, but not in the post-test[54] and in the delayed post-test[55]. There are no significant[56] gender effects in the tests. The mean ranks in the post-test are significantly[57] higher than in the pre-test for all three experiments (figure 4). Only for the group in exp1 there is a significantly[58] lower mean rank in the delayed post-test compared to the post-test.

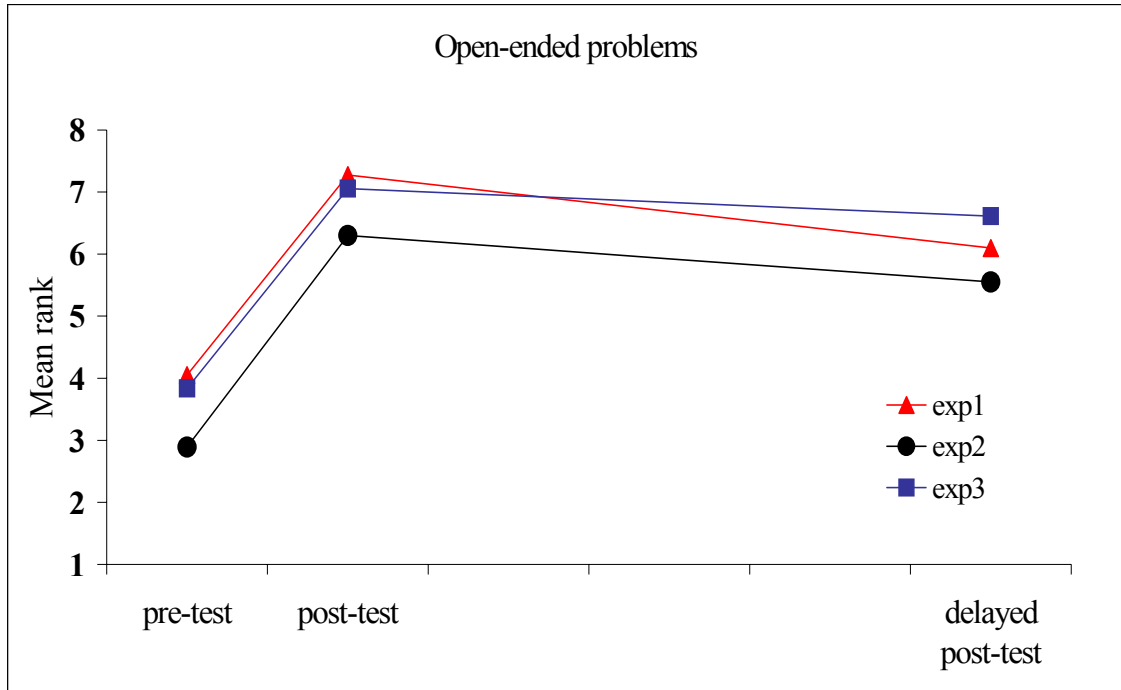[53] Kruskal-Wallis one-way test; p(pre-test)=0,004**
[54] Kruskal-Wallis one-way test; p(post-test)=0,080
[55] Kruskal-Wallis one-way test; p(delayed post-test)=0,051
[56] Kruskal-Wallis one-way test; p(pre-test)=0,263; p(post-test)=0,348; p(delayed post-test)=0,609
[57] Wilcoxons matched-pairs signed-ranks test; p<<0,001***
[58] Wilcoxons matched-pairs signed-ranks test; p(exp1)<<0,001***; p(exp2)=0,096; p(exp3)=0,117

Figur 4. Comparison of group mean ranks of the open-ended problems between pre-test, post-test, and delayed post-test.

Consistency of use of ideas in pre-test and delayed post-test

All answers in the pre-test and delayed post-test are analysed according to their consistency in the use of alternative or scientific ideas. Each answer, out of seven (pre-test) or eight (delayed post-test) possible, is categorized as either alternative (A) or scientific (V). In accordance to this, four categories are created for the whole pre-test and delayed post-test, respectively:

- AA: the test result is consistently alternative and includes no more than one answer with scientific ideas.
- AV: the test result has two to three answers with scientific ideas.
- VA: the test result has four to six answers with scientific ideas.
- VV: the test result is consistently scientific and includes at least seven answers with scientific ideas.

The results of this categorization are shown in table 5. The students, whose pre-test and delayed post-test results have the same category of consistency, end up in the diagonal. These students (23 %) have not evolved their knowing in the theory of evolution, as represented by a higher frequency of scientific answers. Below the diagonal, one student is found having a better performance in the pre-test compared to the delayed post-test. The vast majority of the students, 76 % (60 students), perform better in the delayed post-test.

Table 5. Change in students' consistency in alternative and scientific way of answering in the pre-test and delayed post-test (n=79).

		Pre-test				
		AA	**AV**	**VA**	**VV**	**Σ**
Delayed post-test	**VV**	20	3	7	4	34
	VA	13	7	3	1	24
	AV	10	7			17
	AA	4				4
	Σ	47	17	10	5	79

Individual development of knowing about evolution

The students' development is described from pre-test and interviews before teaching, through the teaching sequence and until the delayed post-test. During teaching students in exp1 and exp2 were interviewed. The students in exp3 performed small-group discussions and were answering an individual database-driven Internet problem. The students' overall performance, taken together, shows the different preconceptions with which the students entered the teaching sequence, and their knowing about evolution during and after teaching. In table 5 results from pre- and delayed post-test exclusively are considered. Taking the students' results from all data collections into consideration motivates some change of table 5. The net result is that the delayed post-test VV-sum changes from 34 to 39, and the delayed post-test VA-sum from 24 to 19.

Many students enter the teaching sequence with alternative ideas about evolution that are not in agreement with the scientific ones. They see evolution as a gradual process where every member of the population adapts to the environment. They consider adaptation as the driving force that is regulated by, for instance need, strive or purpose. From this starting point, the majority of the students reach a scientific level and increase their scientific understanding of the theory of evolution, but some students do not.

In the analyses, some possible obstacles for understanding the theory of evolution are identified:
- lack of acceptance of chance events
- religious belief
- learning a 'standard' answer
- alternative ideas

Discussion

The proportion of students answering the 'cheetah' problem with exclusively scientific ideas increased between pre-test and delayed post-test from 27 %, 0 %, and 28 % in the three experiments to 78 %, 75 %, and 89 % respectively. This latter result can be considered good for different reasons: the delayed post-test is performed one year after teaching; the students know that their result doesn't affect their grade in biology; and the results are good in comparison with other studies in the literature. This 'cheetah' problem has been used in many investigations as described before. Bishop and Anderson (1990) find an increase of scientific answers to this problem from 25 % to 50 % between pre- and post-test. Demastes, Settlage and Good (1995) repeat the study of Bishop and Anderson, but their students are less successful in giving scientific answers. Bizzo (1994) uses this problem with students between 15 and 17 years old after they have been taught evolution, and 28 % of the students' answers include chance and selection. Jensen and Finley (1995) use similar problems with university students' and report an increase of scientific answers from 23 % in the pre-test to 45 % in a delayed post-test administered after 2 weeks. There are few examples of good long-term retention in the literature. One is a study by Jiménez-Aleixandre (1992), who performed a delayed post-test one year after teaching. In her experimental group on average 60 % of the 14-year-old students answered the problems scientifically.

In the category VA the students' answers are predominantly scientific and can together with the students in the VV category be considered having scientific reasoning (table 5). This means that almost three quarters of the students answer scientifically, or 58 students out of 79. The majority of the students have alternative ideas about evolution before teaching (category AA and AV, 64 students out of 79, table 5). Several students do not accept random processes before teaching, which they told us through the pre-test or in the interviews. These students find it absurd that the diversity and the complexity of life is the result of such a process. In the interviews during teaching, as in the post-test and the delayed post-test, almost every student accepts random mutations. In the teaching sequence we took note of the recommendation from Bishop and Anderson (1990) and explicitly divided evolutionary process into two: the origin of variation and natural selection. To make a point of the fact that not the entire evolutionary process is a random process seems to be one of the reasons for the success of our students in understanding and applying the theory of evolution.

In the open-ended problems it becomes obvious that if a student is reasoning about existing variation in a population he/she also uses differences in

survival rate among individuals. The reasoning about existing variation is not always well developed and sometimes more or less implicit, but to be aware of the existence of variation in a given characteristic among the individuals seems to be a key idea for scientific reasoning about evolution. Several authors write that their students in both secondary school and in universities don't give attention to intraspecific variation (e.g. Deadman & Kelly, 1978; Brumby, 1984; Bishop & Anderson, 1990; Greene, 1990; Demastes, Settlage & Good, 1995). Intraspecific variation is troublesome also after teaching, as shown by Jensen and Finley (1995) and Smith, Siegel and McInerney (1995). This points out the importance of discussing intraspecific variation within populations in detail during a teaching sequence. Zetterqvist (2003) interviewed 26 experienced teachers (grade 7 to 9) about their teaching of evolution. She asked the teachers to describe the different aspects of evolution that they include, and only two of these teachers talked spontaneously about variation within populations. Then, answering a direct question, the majority said that they taught about variation, and six of these teachers mention that they used variation in connection with natural selection.

The results from the written tests are confirmed in the analyses of individual interviews and small group discussions. The following joint results emerge from the different analyses:

- all students do not accept random processes before teaching
- existing variation is a key idea for understanding the theory of evolution
- several students do not realize the importance of reproductive rate for characters to evolve
- many students use 'need' without meaning that the process of evolution is need-driven
- the evolutionary meaning of adaptation is difficult
- many students use the same alternative ideas
- the students interpret the problems on different levels of biological organisation

Many authors give attention to students' inexperience with intraspecific variation, as discussed earlier, but do not directly point out its general importance. I see the existing variation as the key idea for scientific understanding of the theory of evolution. Through existing variation the students seem to be able to reason scientifically. This is a consistent result from analyses of open-ended problems in the written tests, from interviews, from small group discussions, and from the database-driven Internet problem. In the interviews about natural selection, in the group discussions, and in the Internet problem the students were shown the existing variation explicitly

and all students or groups of students do reason about differential survival rates among individuals. All students who write about existing variation in the test problems also give attention to differences in survival rates.

The combined results from the analyses of the three experiments can be summarized in a domain specific hypothesis for teaching evolutionary biology.

PART V: DOMAIN SPECIFIC HYPOTHESIS

I have used the results above to formulate a hypothesis, which can be tested in new design experiments, and if it will withstand future tests it can be developed into a domain specific theory for teaching evolutionary biology. Before we designed the teaching in each of the three experiments, we formulated a hypothesis, although we did not use this term at that time. By performing exp1 and exp2 the early hypothesis was tested. We used the results to reformulate it before teaching in exp3. It was then tested and further developed through the results and analyses in this thesis. I now consider this a more comprehensive, testable hypothesis. In this hypothesis I bring up aspects from this thesis, other research, and insights I have found important for understanding biological evolution in general and the theory of evolution in particular. The intention is to specify conditions that facilitate learning with understanding, in this case evolution. Understanding this theory means being able to use the theory to describe, understand, explain, and partly predict biological phenomena. In this part, the last research question will be addressed: 'How can a domain specific hypothesis for teaching about biological evolution be characterised?'.

A more comprehensive hypothesis for teaching biological evolution

The present hypothesis for teaching biological evolution has three different aspects:
1. Content specific aspects
2. Aspects concerning the nature of science
3. General aspects

Every field of science has its own, unique content specific aspects. The aspects concerning the nature of science are more or less common for all teaching in the natural sciences. The general aspects may also be valid for teaching subjects other than the natural sciences.

If the following aspects are considered in teaching, the students' opportunity to learn and understand the theory of evolution and its consequences will be improved:

A. Content specific aspects

1. The teaching takes a staring point in evolution as a scientific historical fact, the origin of life is discussed, and evolutionary time is concretized.
2. The theory of evolution is divided into two processes, the origin of variation and natural selection.
3. It is emphasized that only the first of these is a random process and not natural selection.
4. Common alternative ideas about biological evolution, such as the idea about need-driven adaptation of all individuals in a species to the environment, become in a suitable manner part of the teaching content.
5. The theory of evolution is studied through introduction, discussion, and application of five central components: 'variation', 'heredity', 'survival', 'reproduction' and 'accumulation'.
   - Existing variation is discussed in detail and as much genetics are included as needed to get an idea about how similarities and differences appear.
   - Differences in survival and in reproduction among the individuals in the population are discussed, and how these differences are related to natural selection.
   - The adaptation of specific traits through accumulation is discussed.
6. The awareness about existing variation of inheritable characters is a necessary key idea for going on to natural selection and by that create an alternative to ideas about evolution being caused by needs, strives, wishes, and so on.
7. Different levels of biological organisation are expressed explicitly in evolutionary reasoning.
8. The theory of evolution through natural selection is used to explain the development of life, biological diversity, sexual selection, co-evolution, speciation, behavioural ecology, ethology and so on.

B. Aspects concerning the nature of science

1. The nature of science is made explicit (hypothetical in nature, can be used to explain and predict, can be tested in experiments and by observations, can not be verified to the extent of being absolutely true, gives a consistent understanding of many phenomena and so on).
2. The differences between science and faith are discussed. Especially in teaching evolution: Science has nothing to say about the existence of God or His actions and therefore does not have to be an immediate threat against religious beliefs. This insight can contribute to solve

the problem that religious beliefs can obstruct the learning of evolutionary theory.

3. The students are invited to take part in the way science explains phenomena in the world, in this case the origin of life and how the species have evolved and is evolving. Great respect is shown the students who have alternative ideas about this subject.

C. General aspects

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

2. The teacher is well informed about common alternative ideas in the content area and their significance for teaching. Teachers are aware of these ideas through the whole teaching sequence. He/she is paying attention to and is interested in the students' alternative ideas, both well known as well as new ones.

3. The teacher creates an allowing classroom climate so the students feel free to share their ideas and thoughts in a positive way. It is these ideas that are met and scrutinized in discussions, rather than the students or the students and the teachers.

4. Time and care is given to the basic concepts in the actual topic.

5. Extensive time is used to discuss and solve concrete problems, which make the students familiar in using the taught content.

6. Deep learning is stimulated. Signs of this are for example that the students:
   - 'toss and turn' the new information (transformation instead of memorising)
   - ask questions and throwing out suggestions
   - connect new and existing knowing
   - use what has been learned as a tool to see ones world in a new way
   - discuss the new knowing with mates and others
   - engage in challenges (e.g. problem solving)

7. Formative assessment is used by both students and teachers with the aim of improving learning and teaching in a variable manner.

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

REFERENSER

AAAS. American Association for the Advancement of Science (1993). *Benchmarks for science literacy. Project 2061*. New York: Oxford University Press.

AAAS. American Association for the Advancement of Science (1990). *Science for all americans. Project 2061*. New York: Oxford University Press.

AAAS. American Association for the Advancement of Science (2003). Hemsidan tillgänglig [20031118] på http://www.aaas.org/

Adawi, T. (2002). *From branes to brains: On M-theory and understanding thermodynamics*. (Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 2). Uppsala: Acta Universitatis Upsaliensis.

Aikenhead, G. (2000). Renegotiating the culture of school science. In Miller, R., Leach, J., & Osborne, J. (Eds.), *Improving science education - the contribution of research* (pp. 245-264). Buckingham: Open University Press.

Albaladejo, C., & Lucas, A. M. (1988). Pupils' meanings for 'mutation'. *Journal of Biological Education, 22*(3), 215-219.

Alles, D. L. (2001). Using evolution as the framework for teaching biology. *The American Biology Teacher, 63*(1), 20-23.

Anderson, C. W., & Hogan, K. (1999). Editorial and call for papers: Design in Science Education. *Journal of Research in Science Teaching, 36*(9), 975-976.

Anderson, D. L., Fisher, K. M., & Norman, G. J. (2002). Development and evaluation of the conceptual inventory of natural selection. *Journal of research in science teaching, 39*(10), 952-978.

Anderson, R. D., & Helms, J. V. (2001). The ideal of standards and the reality of schools: Needed research. *Journal of Research in Science Teaching, 38*(1), 3-16.

Andersson, B. (2000a). *Om ämnesdidaktikens natur, kultur och värdegrund*. Opubliserat manuskript, Göteborg: Göteborgs universitet, Institutionen för pedagogik och didaktik.

Andersson, B. (2000b). National evaluation for improvment of science teaching. In Miller, R., Leach, J., & Osborne, J. (Eds.), *Improving science education - the contribution of research* (pp. 62-78). Buckingham: Open University Press.

Andersson, B. (2001). *Elevers tänkande och skolans naturvetenskap. Forskningsresultat som ger nya idéer*. Stockholm: Liber.

Andersson, B., & Bach, F. (1996). Developing new teaching sequences in science: The example of 'gases and their properties'. In Welford, G., Osborne, J., & Scott, P. (Eds.), *Research in Science Education in Europe* (pp. 7-21). London: The Falmer Press.

Andersson, B., Bach, F., Frändberg, B., Hagman, M., Jansson, I., Kärrqvist, C., et al. (2003). *Att förstå naturen - från vardag till biologi; fyra workshops.* (Vol. 2). Göteborg: Göteborgs Universitet, Institutionen för pedagogik och didaktik.

Andersson, B., Bach, F., Frändberg, B., Jansson, I., Kärrqvist, C., Nyberg, E., et al. (2003a). *Att förstå och använda naturvetenskapen; sju workshops.* (Vol. 1). Göteborg: Göteborgs Universitet, Institutionen för pedagogik och didaktik.

Andersson, B., Bach, F., Frändberg, B., Jansson, I., Kärrqvist, C., Nyberg, E., et al. (2003b). *Att förstå naturen - från vardag till fysik; sex workshops.* (Vol. 3). Göteborg: Göteborgs Universitet, Institutionen för pedagogik och didaktik.

Andersson, B., Bach, F., Frändberg, B., Jansson, I., Kärrqvist, C., Nyberg, E., et al. (2003c). *Att förstå naturen - från vardag till kemi; sex workshops.* (Vol. 4). Göteborg: Göteborgs Universitet, Institutionen för pedagogik och didaktik.

Andersson, B., Bach, F., Hagman, M., Olander, C., & Wallin, A. (2003). *Discussing a rationale for the design of teaching sequences.* Paper presented at the Fourth ESERA Conference, Noordwijkerhout, The Netherlands.

Andersson, B., Bach, F., & Zetterqvist, A. (1996). *Nationell utvärdering 95 - Energi i natur och samhälle.* Göteborg: Göteborgs Universitet, Institutionen för ämnesdidaktik.

Andersson, B., Emanuelsson, J., & Zetterqvist, A. (1993). *Nationell utvärdering 92 – Vad kan eleverna om ekologi och människokroppen?* Mölndal: Göteborgs Universitet, Institutionen för ämnesdidaktik.

Andersson, B., Kärrqvist, C., Löfstedt, A., Oscarsson, V., & Wallin, A. (1999). *Utvärdering av skolan 1998 avseende läroplanens mål (US98). Tema tillståndet i världen.* Stockholm: Skolverket: Liber distribution.

Asimov, I. (1981, June 14). The 'threat' of creationism. *The New York Times Magazine*, 1-4.

Baalmann, W., Frerichs, V., & Illner, R. (1998). Educational reconstruction - examples in the fields of genetics and evolution. In Bayrhuber, H., & Brinkman, F. (Eds.), *What - Why - How?* (pp. 273-282). Kiel: IPN.

Baalmann, W., & Kattmann, U. (2001). Towards a better understanding of genetics and evolution - research in students' conceptions leads to a re-arrangement of teaching biology. In García-Rodeja Gayoso, I.,

Díaz de Bustamante, J., Harms, U., & Jiménez Aleixandre, M.P. *Proceedings from III Conference of European Researchers in Didactic of Biology (ERIDOB)* (pp. 13-25) Spain: Universidade de Santiago de Compostela.

Bach, F. (2001). *Om ljuset i tillvaron. Ett undervisningsexperiment inom optik.* (Göteborg Studies in Educational Sciences 162). Göteborg: Acta Universitatis Gothoburgensis.

Bassey, M. (1981). Pedagogic Research: on the relative merits of search for generalisation and study of single events. *Oxford Review of Education, 7*(1), 73-94.

Bateson, G. (1972). *Steps to an ecology of mind.* New York: Ballantine Books.

Bereiter, C. (2002). *Education and mind in the knowledge age*. Mahwah, NJ: Lawrence Erlbaum Associates.

Bishop, B. A., & Anderson, C. W. (1986). Evolution by natural selection: a teaching module. *Occasional paper No 91*.

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of research in science teaching, 27*(5), 415-427.

Bizzo, N. m. V. (1994). From down house landlord to Brazilian high school students: What has happend to evolutionary knowledge on the way? *Journal of research in science teaching, 31*(5), 537-556.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in Education, 5*(1), 7-73.

Bowden, J., & Marton, F. (1998). *The university of learning. Beyond quality and competence in higher education*. London: Kogan Page.

Brem, S. K., Ranney, M., & Schindel, J. (2003). Perceived consequences of evolution: College students perceive negative personal and social impact in evolutionary theory. *Science Education, 87*(2), 181-206.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challanges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences, 2*(2), 141-178.

Brumby, M. N. (1981). The use of problem-solving in meaningful learning in biology. *Research in Science Education, 11*, 103-110.

Brumby, M. N. (1984). Misconceptions about the concept of natural selection by medical biology students. *Science Education, 68*(4), 493-503.

BSCS. (1992). *Biological science. An ecological approach*. Dubuque, Iowa: Kendall/Hunt Publishing Company.

Caravita, S., & Halldén, O. (1994). Re-framing the problem of conceptual change. *Learning and Instruction, 4,* 89-111.

Chalmers, A. F. (1994). *Vad är vetenskap egentligen? Om väsen och status hos vetenskapen och dess metoder*. Nora: Bokförlaget Nya Doxa.

Chi, M. T. H. (1997). Creativity: shifting across ontological categories flexibly. In Ward, T. B., Smith, S.M. & Vaid, J. (Eds.), *Creative Thought: An Investigation of Conceptual Structures and Processes* (pp. 209-234). Washington DC: American Psychological Association.

Claesson, S. (2002). *Spår av teorier i praktiken. Några skolexempel.* Lund: Studentlitteratur.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design Experiments in Educational Research. *Educational Researcher, 32*(1), 9-13.

Cobern, W. W. (1994). Point: Belief, understanding, and the teaching of evolution. *Journal of research in science teaching, 31*(5), 583-590.

Cochran, K. F., DeRuiter, J. A., & King, R. A. (1993). Pedagogical content knowing: An integrative model for teacher preparation. *Journal of Teacher Education, 44*(4), 263 - 272.

Crooks, T. J. (1988). The impact of classroom evaluation practices on students. *Review of Educational Research, 58*, 438-481.

Cummins, C. L., Demastes, S. S., & Hafner, M. S. (1994). Evolution: Biological education´s under-researched unifying theme. *Journal of research in science teaching, 31*(5), 445-448.

Dagher, Z., & BouJaoude, S. (1997). Scientific views and religious beliefs of college students: The case of biological evolution. *Journal of Research in Science Teaching, 34*(5), 429-445.

Darwin, C. (1859). *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.* Hemsidan tillgänglig [2004-01-17] på http://www.literature.org/ authors/darwin-charles/the-origin-of-species/

Deadman, J. A., & Kelly, P. J. (1978). What do secondary school boys understand about evolution an heredity before they are taught the topics ? *Journal of Biological Education, 12*(1), 7-15.

Demastes, S. S., Good, R., & Peebles, P. (1995). Students' conceptual ecologies and the process of conceptual change in evolution. *Science Education, 79*(6), 637-666.

Demastes, S. S., Good, R., & Peebles, P. (1996). Patterns of conceptual change in evolution. *Journal of Research in Science Teaching, 33*(4), 407-431.

Demastes, S. S., Settlage, J., & Good, R. (1995). Students' conceptions of natural selection and its role in evolution: Cases of replication and comparison. *Journal of Research in Science Teaching, 32*(5), 535-550.

the Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Reseacher, 32*(1), 5-8.

DeVore, I., Goethals, G. W., & Trivers, R. L. (1974). *Exploring human nature. Unit 1: Origins of human behavior*. Cambridge, Massachusetts: Education Development Center.

Dodick, J., & Orion, N. (2003). Cognitive factors affecting student understanding of geologic time. *Journal of Research in Science Teaching, 40*(4), 415-442.

Downie, J. R., & Barron, N. J. (2000). Evolution and religion: attitudes of Scottish first year biology and medical students to the teaching of evolutionary biology. *Journal of Biological Education, 34*(3), 139-146.

Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher, 23*(7), 5-12.

Duit, R. (1999). Conceptual change approaches in science education. In Schnotz, W., Vosniadou, S., & Carretero, M. (Eds.), *New perspectives on conceptual change* (pp. 263-282). Oxford, UK: Pergamon.

Duit, R. (2000). *A model of educational reconstruction as a framework for designing and validating teaching and learning sequences.* Paper presented at the The International Symposieum 'Designing and Validating Teaching-Learning Sequences in a Research Perspective', Paris.

Duit, R. (2001). Educational Reconstruction: Science subject matter and educational issues in harmony - Research and development intimately linked. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 2* (pp. 227-229). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Duit, R. (2004). *Bibliography – STCSE: Students' and teachers' conceptions and science education,* Hemsidan tillgänglig [2004-04-23] på http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html

Duit, R., & Treagust, D. F. (2003). Conceptual change: a powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*(6), 671-688.

Dunbar, R. (1995). *The trouble with science*. London: Faber and faber.

Ekborg, M. (2002). *Naturvetenskaplig utbildning för hållbar utveckling? En longitudinell studie av hur studenter på grundskollärarprogrammet utvecklar för miljöundervisning relevanta kunskaper i naturkunskap.* (Göteborg Studies in Educational Sciences 188). Göteborg: Acta Universitatis Gothoburgensis.

EKNA. (1979-1989). *'Elevtänkande och Kurskrav i högstadiets NAturvetenskapliga undervisning*, Hemsidan tillgänglig [2003-12-29] på http://na-serv.did.gu.se/nadpub/epersp.html

Emanuelsson, J. (2001). *En fråga om frågor. Hur lärares frågor i klassrummet gör det möjligt att få reda på elevernas sätt att förstå det som undervisningen behandlar i matematik och naturvetenskap.* (Göteborg Studies in Educational Sciences 168). Göteborg: Acta Universitatis Gothoburgensis.

Engel Clough, E., & Driver, R. (1986). A study of consistency in the use of students' conceptual frameworks across different task contexts. *Science Education, 70*(4), 473-496.

Engel Clough, E., & Wood-Robinson, C. (1985a). How secondary students interpret instances of biological adaptation. *Journal of Biological Education, 19*(2), 125-130.

Engel Clough, E., & Wood-Robinson, C. (1985b). Children's understanding of inheritance. *Journal of Biological Education, 19*(4), 304-310.

Erickson, G. (2000). Research programmes and the student science learning literature. In Miller, R., Leach, J., & Osborne, J. (Eds.), *Improving science education - the contribution of research* (pp. 271-292). Buckingham: Open University Press.

Fagerström, T. (1995). *Den skapande evolutionen. Om vad evolutionsteorin innebär - och inte innebär.* Lund: ScUP Scandinavian University Press.

Falconer, D. S. (1981). *Introduction to quantitative genetics.* London: Longman.

Ferrari, M., & Chi, M. T. H. (1998). The nature of naive explanations of natural selection. *International Journal of Science Education, 20*(10), 1231-1256.

Furth, H. G. (1969). *Piaget and knowledge theoretical foundations.* New Jersey: Prentice-Hall, Inc., Englewood Cliffs.

Good, R., Trowbridge, J., Demastes, S., Wandersee, J., Hafner, M., & Cummins, C. (1992). *Proceedings of the 1992 Evolution Education Research Conference.* Baton Rouge: Lousiana State University.

Greene, E. D. (1990). The logic of university students' misunderstanding of natural selection. *Journal of Research in Science Teaching, 27*(9), 875-885.

Gropengiesser, H. (1998). What language reveals about our conceptions - A case study on seeing. In Komorek, M., Behrendt, H., Dahncke, H., Duit, R., Graeber, W., & Kross, A. (Eds.), *Research in Science Education - Past, Present, and Future Vol.1* (pp. 140-142). Kiel: IPN Kiel.

Grose, E. C., & Simpson, R. D. (1982). Attitudes of introductory college biology students toward evolution. *Journal of Research in Science Teaching, 19*(1), 15-24.

Gustafsson, J.-E., & Myrberg, E. (2002). *Ekonomiska resursers betydelse för pedagogiska resultat - en kunskapsöversikt.* Stockholm: Liber.

Gustavsson, B. (2000). *Kunskapsfilosofi: Tre kunskapsformer i historisk belysning.* Stockholm: Wahlström & Widstrand.

Hagman, M., Olander, C., & Wallin, A. (2001). Teaching and learning about the biological evolution: A preliminary teaching learning sequence. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 1* (pp. 230-232). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Hagman, M., Olander, C., & Wallin, A. (2003). Research-based teaching about biological evolution. In Lewis, J., Margo, A., & Simonneaux, L. (Eds.) *Biology education for the real world. Student - Teacher – Citizen. Proceedings of the IV Conference of European Researchers in Didactic of Biology (ERIDOB)* (pp. 105-119) Toulouse – France: Ecole national de formation agronomique.

Halldén, O. (1988). The evolution of the species: pupil perspectives and school perspectives. *International Journal of Science Education, 10*(5), 541-552.

Halldén, O. (1999). Conceptual change and contextualization. In Schnotz, W., Vosniadou, S., & Carretero, M. (Eds.), *New perspectives on conceptual change* (pp. 53-66). Oxford, UK: Pergamon.

Helldén, G., & Solomon, J. (in press). The persistence of personal and social themes in context: Long and short term studies of students' scientific ideas. *Science Education.*

Hewson, P., W. (1981). A conceptual change approach to learning science. *European Journal of Science Education, 3*(4), 383-396.

Hewson, P. W., Beeth, M. E., & Thorley, N. R. (1998). Teaching for conceptual change. In Fraser, B. J. & Tobin, K. G (Eds.) *Internatioal handbook of science education*, 199-218.

Hewson, P. W., & Lemberger, J. (2000). Status as the hallmark of conceptual learning. In Miller, R., Leach, J., & Osborne, J. (Eds.), *Improving science education - the contribution of research* (pp. 110-125). Buckingham: Open University Press.

Hiebert, J., Gallimore, R., & Stigler, J.W. (2002). A Knowledge Base for the Teaching Profession: What Would It Look Like and How Can We Get One? *Educational Researcher, 31*(5), 3-15.

Husén, T. (1994). *Nationalencyklopedien*, Hemsidan tillgänglig [2004-01-16] på http://www.ne.se/jsp/search/article.jsp?i_art_id=281118&i_word=pedagogik.

Jensen, M. S., & Finley, F. N. (1995). Teaching evolution using historical arguments in a conceptual change strategy. *Science Education, 79*(2), 147-166.

Jensen, M. S., & Finley, F. N. (1996). Changes in students´ understanding of evolution resulting from different curricular and instructional strategies. *Journal of research in science teaching, 33*(8), 879-900.

Jimenez-Aleixandre, M. P. (1992). Thinking about theories or thinking with theories?: a classroom study with natural selection. *International Journal of Science Education, 14*(1), 51-61.

Jimenez-Aleixandre, M. P. (1994). Teaching evolution and natural selection: A look at textbooks and teachers. *Journal of Research in Science Teaching, 31*(5), 519-535.

Jungwirth, E. (1975). 'Preconceived adaption and inverted evolution' - A case of distorted concept-formation in high school biology. *The Australian Science Teachers Journal, 21*(2), 95-100.

Kansanen, P. (1999). The *Deutsche Didaktik* and the American research on teaching. *TNTEE Publications, 2*(1), 21-35.

Kargbo, D. B., Hobbs, E. D., & Erickson, G. L. (1980). Children's beliefs about inherited characteristics. *Journal of Biological Education, 14*(2), 137-146.

Karlsson, J., Krigsman, T., Molander, B-O., & Wickman, P-O. (1994). *Biologi 1 med naturkunskap för gymnasieskolan*. Stockholm: Liber Utbildning.

Karmiloff-Smith, A. (1992). *Beyond modularity. A developmental perspective on cognitive science*. Cambridge, Massachusetts: The MIT Press.

Kattmann, U., Duit, R., & Gropengiesser, H. (1998). The model of educational reconstruction - bringing together issues of scientific clarification and students´ conceptions. In Bayrhuber, H., & Brinkman, F. (Eds.), *What - Why - How? Research in Didaktik of Biology* (pp. 253-262). Kiel: IPN - Materilien.

Kattmann, U., Duit, R., Gropengiesser, H., & Komorek, M. (1997). Das Modell der Didaktischen Rekonstruktion - Ein Rahmen fuer naturwissenschaftsdidaktische Forschung und Entwicklung. *Zeitschrift fuer Didaktik der Naturwissenschaften, 3*(3), 3-18.

Keown, D. (1988). Teaching evolution. *The American Biology Teacher, 50*(7), 407-410.

Klaassen, C. W. J. M., & Lijnse, P. L. (1996). Interpreting students' and teachers' discourse in science classes: An underestimated problem? *Journal of Research in Science Teaching, 33*(2), 115-134.

Knippels, M. C. P. J., Waarlo, A. J., & Boersma, K. Th. (2001). The 'yo-yo strategy' for learning and teaching genetics in upper-secondary biology education. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 2* (pp. 477-479). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Knippels, M.-C. P. J. (2002). *Coping with the abstract and complex nature of genetics in biology education. The yo-yo learning and teaching strategy.* Doktorsavhandling, Utrecht: Universiteit Utrecht.

Kroksmark, T. (1989). *Didaktiska strövtåg. Didaktiska idéer från Comenius till fenomengrafisk didaktik.* Göteborg: Daidalos.

Kuhn, T. S. (1992). *De vetenskapliga revolutionernas struktur*. Stockholm: Thales.

Kvale, S. (1997). *Den kvalitativa forskningsintervjun*. Lund: Studentlitteratur.

Kärrqvist, C. (1985). *Kunskapsutveckling genom experimentcentrerade dialoger i ellära.* (Göteborg Studies in Educational Sciences 52). Göteborg: Acta Universitatis Gothoburgensis.

Lakoff, G., & Johnsson, M. (1999). *Philosophy in the flesh - the embodied mind and its challenge to western thought*. New York: Basic Books.

Landström, J. (1995). '… djur kan ju inte bildas ur tomma intet'. Elever skriver om djurenss evolution. I B. Andersson (Ed.) Forskning om naturvetenskaplig undervisning. NA-SPEKTRUM nr 15 (pp. 83-104). Mölndal: Göteboegs universitet, Institutionen för ämnesdidaktik.

Landström, J. (1999). Evolutionen bara en teori ...? Hur blivande lärare i baturvetenskap uppfattar begreppen naturlag och teori samt hur de bedömer utsagor om evolutionsteorin och bibelns skapelseberättelse. I L. Aho, & J. Viiri (Eds.) *Undervisning i naturvetenskap ur kultur-, teknologi- och miljöperspektiv* (pp.249-260) Joensuu: Joensuu universitet.

Larsson, S. (1994). Om kvalitetskriterier i kvalitativa studier. I. B. Starrin & P-G Svensson (Eds.) *Kvalitativ metod och vetenskapsteori.* (pp. 163-189) Lund: Studentlitteratur.

Lawson, A. E., & Thompson, L. D. (1988). Formal reasoning ability and misconceptions concerning genetics and natural selection. *Journal of Research in Science Teaching, 25*(9), 733-746.

Lawson, A. E., & Weser, J. (1990). The rejection of nonscientific beliefs about life: Effects of instruction and reasoning skills. *Journal of Research in Science Teaching, 27*(6), 589-606.

Lawson, A. E., & Worsnop, W. A. (1992). Learning about evolution and rejecting a belief in special creation: Effects of reflective reasoning skill, prior knowledge, prior belief and religious commitment. *Journal of Research in Science Teaching, 29*(2), 143-166.

Leach, J., & Scott, P. (2002). Designing and evaluating science teaching sequences: An approach drawing upon the concept of learning demand and a social constructivist perspective on learning. *Studies in Science Education, 38*, 115-142.

Leach, J., & Scott, P. (2003). Individual and sociocultural views of learning in science education. *Science & Education, 12*(1), 91-113.

Lemke, J. L. (1993). *Talking Science. Language, Learning, and Values*. Norwood, New Jersey: Ablex Publishing Corporation.

Lijnse, P. L. (1995). 'Development research' as a way to an empirically based 'didactical structure' of science. *Science Education, 79*(2), 189-199.

Lijnse, P. (2000). Didactics of science: the forgotten dimension in science education research? In Miller, R., Leach, J., & Osborne, J. (Eds.), *Improving science education - the contribution of research* (pp. 308-326). Buckingham: Open University Press.

Lijnse. (2003). *Reflections on a problem posing approach*. Paper presented at the Fourth ESERA Conference, Noordwijkerhout, The Netherlands.

Linder, C. J. (1993). A challenge to conceptual change. *Science Education, 77*(3), 293-300.

Maret, T. J., & Rissing, S. W. (1998). Exploring genetic drift & natural selection through a simulation activity. *The American Biology Teacher, 60*(9), 681-683.

Marton, F., & Booth, S. (2000). *Om lärande*. Lund: Studentlitteratur.

Marton, F., & Morris, P. (2002). What matters? In Marton, F., & Morris P. (Eds.), *What Matters? Discovering critical conditions of classroom learning* (Vol. 181, pp. 133-143). Göteborg: Acta Universitatis Gothoburgensis.

Mayr, E. (1997). *This is Biology. The Science of the Living World*. Cambridge, Massachusetts: Harvard University Press.

Meadows, L., Doster, E., & Jackson, D. F. (2000). Managing the conflict between evolution & religion. *The American Biology Teacher, 62*(2), 102-107.

Méheut, M. (2000). *Teaching-learning sequences and research: A dual perspective*. Paper presented at the The International Symposieum 'Designing and Validating Teaching-Learning Sequences in a Research Perspective', Paris.

Meheut, M. (2001). Two aspects of the relations between research and development. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 1* (pp. 239-241). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Méheut, M., & Psillos, D. (2004). Teaching-learning sequences: aims and tools for science education research. *International Journal of Science Education, 26*(5), 515-535.

Millar, R. (1989). Constructive criticisms. *International Journal of Science Education, 11*, 587-596.

Moore, R. (1998a). Creationism in the United States. I: Banning evolution from the classroom. *The American Biology Teacher, 60*(7), 486-507.

Moore, R. (1998b). Creationism in the United States. II: The aftermath of the Scopes trial. *The American Biology Teacher, 60*(8), 568-577.

Moore, R. (1998c). Creationism in the United States. III: The ban on the teaching of evolution reaches the U.S. supreme court. *The American Biology Teacher, 60*(9), 650-661.

Moore, R. (1999a). Creationism in the United States. IV: The aftermath of Epperson v. Arkansas. *The American Biology Teacher, 61*(1), 10-16.

Moore, R. (1999b). Creationism in the United States. V: The McLean decision destroys thec of 'creation science'. *The American Biology Teacher, 61*(2), 92-101.

Moore, R. (1999c). Creationism in the United States. VI: Demanding balanced treatment. *The American Biology Teacher, 61*(3), 175-180.

Moore, R. (1999d). Creationism in the United States. VII: The lingering impact of inherit the wind. *The American Biology Teacher, 61*(4), 246-250.

Moore, R. (1999e). Creationism in the United States. VIII: The lingering threat. Evolutionary biology continues to face opposition, while creationism increases in popularity. *The American Biology Teacher, 61*(5), 330-340.

Mortimer, E. (1995). Conceptual change or conceptual profile change? *Science & Education, 4*(3), 267-285.

NAS. National Academy of Science. (1998). *Teaching about evolution and the nature of science*. Washington, DC: National Academy Press.

Naturhistoriska museet och Utbildningsförvaltningen. (2004) *Historien om livet på jorden.* Hemsidan tillgänglig [2004-02-11] på http://www.gnm.se/evolution/index.htm

Ogborn, J. (1997). Constructivist metaphors of learning science. *Science & Education, 6*(1-2), 121-133.

Olander, C. (2003). *Hur uppstår biologisk variation? En studie av gymnasieelevers uppfattningar och hur de utvecklas genom undervisning.* (IPD-rapport (NA-spektrum nr 23) Nr. 2003:10), Göteborg: Göteborgs universitet, Institutionen för pedagogik och didaktik.

Olander, C., Hagman, M., & Wallin, A. (2001). Teaching and learning about biological evolution: A research based teaching-learning sequence. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 2* (pp. 576-578). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Paludan, K. (2000). *Videnskaben verden og vi. Om naturvidenskab og hverdagstænkning*. Århus: AArhus Universitetsforlag.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. *Journal of Research in Science Teaching, 39*(3), 185-204.

Pedersen, S. (1992). *Om elevers förståelse av naturvetenskapliga förklaringar och biologiska sammanhang* (Vol. 31). Stockholm: Almqvist & Wiksell.

Pedersen, S., & Halldén, O. (1994). Intuitive ideas and scientific explanations as parts of students' developing understanding of biology: The case of evolution. *European Journal of Phychology of Education, IX*(1), 127-137.

Pintrich, P. R. (1999). Motivational beliefs as resources for and constraints on conceptual change. In Schnotz, W., Vosniadou, S., & Carretero, M. (Eds.), *New perspectives on conceptual change* (pp. 33-50). Oxford, UK: Pergamon.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167-199.

Popper, K. R. (1972). *Objektive knowledge. An evolutionary approach*. Oxford, UK: Clarendon Press.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Ramorogo, G., & Wood-Robinson, C. (1995). Batswana children's understanding of biological inheritance. *Journal of Biological Education, 29*(1), 60-71.

Redfors, A., & Ryder, J. (2001). University physics students' use of models in explanations of phenomena involving interactions between metals and electromagnetic radiation. *International Journal of Science Education, 23*(12), 1283-1301.

Renström, L., Andersson, B., & Marton, F. (1990). Students' Conceptions of Matter. *Journal of Educational Psychology, 82*(3), 555-569.

Reuterberg, S-E. (1996). *Pedagogiska mätningar: Skalor – reliabilitet – validitet*. Mölndal: Institutionen för pedagogik.

Ridley, M. (1996). *Evolution*. Abingdon, England: Blackwell Science.

Rudolph, J. L., & Stewart, J. (1998). Evolution and the nature of science: On the historical discord and its implications for education. *Journal of Research in Science Teaching, 35*(10), 1069-1090.

Runesson, U., & Marton, F. (2002). The object of learning and the space variation. In Marton, F., & Morris, P. (Eds.), *What matters? Discov-*

ering critical conditions of classroom learning (Vol. 181, pp. 19-37). Göteborg: Acta Universitatis Gothoburgensis.

Sanders, M. (1993). Erroneous ideas about respiration: The teacher factor. *Journal of Research in Science Teaching, 30*(8), 919-934.

Schoultz, J. (2000). *Att samtala om/i naturvetenskap.* Doktorsavhandling, Linköping: Linköpings universitet.

Seel, H. (1999). Didaktik as the professional science of teachers. *TNTEE Publications,* 2(1), 85-93.

Settlage, J. (1994). Conceptions of natural selection: A snapshot of the sense-making process. *Journal of Research in Science Teaching, 31*(5), 449-457.

Sfard, A. (1998). On two metaphors for learning and the dangers of choosing just one. *Educational Researcher, 27*(2), 4-13.

Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 451-462.

Siegel, S. (1956). *Nonparametric statistics for the behavioural sciences.* Kogakusha: McGraw-Hill.

Sinclair, A., Pendarvis, M. P., & Baldwin, B. (1997). The relationship between college zoology students´beliefs about evolutionary theory and religion. *Journal of Research and Developement in education 30:2, 118-125, 30*(2), 118-125.

Sjøberg, S. (1996). Science education research in Europe: Some reflections for the future association. In Welford, G., Osborne, J., & Scott, P. (Eds.), *Research in Science Education in Europe* (pp. 399-404). London: The Falmer Press.

Sjøberg, S. (2000). *Naturvetenskap som allmänbildning - en kritisk ämnesdidaktik.* Lund: Studentlitteratur.

Skolverket. (1999). Kursplaner 1999/2000. Hemsidan tillgänglig [2003-12-30] på http://www.skolverket.se/

Skolverket. (2000). Kursplaner 1999/2000. Hemsidan tillgänglig [2003-12-30] på http://www.skolverket.se/

Skolverket. (2003). KURSINFO 2003/2004. Hemsidan tillgänglig [2003-12-30] på http://www.skolverket.se/

Smith, M. U. (1994). Counterpoint: Belief, understanding, and the teaching of evolution. *Journal of Research in Science Teaching, 31*(5), 591-597.

Smith, M. U., Siegel, H., & McInerney, J. D. (1995). Foundational issues in evolution education. *Science & Education, 4*, 23-46.

Snedecor, G. W., & Cochran, W. G. (1967). *Statistical methods.* Iowa: The Iowa State University Press Ames.

Solomon, J. (1983). Learning about energy: How pupils think in two domains. *European Journal of Science Education, 5*(1), 49-59.

Solomon, J. (1984). Promts, cues and discrimination: the utilization of two seperate knowledge systems. *European Journal of Science Education, 6*(3), 277-284.

Stavy, R., Tirosh, D., & Tsamir, P. (2000). *Teaching sequences based on the intuitive rules theory.* Paper presented at the Designing and evaluating teaching sequences, Univesity of Paris VII Denis Diderot.

Stigler, J. W., & Hiebert, J. (1999). *The teaching gap.* New York: Free Press.

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. *In Duschl, R.A.; Hamilton, R.: Philosophy of science, cognitive science, and educational theory and practice (working title). Albany*, 147-176.

Säljö, R. (1999). Concepts, cognition and discourse: From mental structures to discoursive tools. In Carretero, M. (Ed.), *New Perspectives on Conceptual Change.* Oxford: Pergamon.

Säljö, R. (2000). *Lärande i praktiken. Ett sociokulturellt perspektiv.* Stockholm: Prisma.

Tamir, P., & Zohar, A. (1991). Anthropomorphism and teleology in reasoning about biological phenomena. *Science Education, 15*, 57-68.

Thomas, J. (2000). Learning about genes and evolution through formal and informal education. *Studies in Science Education, 35*, 59-92.

Tiberghien, A. (1996). Construction of prototypical situations in teaching the concepts of energy. In Welford, G., Osborne, J., & Scott, P. (Eds.), *Research in Science Education in Europe* (pp. 100-114). London: The Falmer Press.

Tiberghien, A. (2000). Designing teaching situations in the secondary school. In Miller, R., Leach, J., & Osborne, J. (Eds.), *Improving science education - the contribution of research* (pp. 27-47). Buckingham: Open University Press.

Turmo, A. (2003). *Naturfagdidaktikk og internasjonale studier.* Doktorsavhandling, Oslo: Universitetet i Oslo.

Wallin, A. (1988). The genetics of foraging behaviour: Artificial selection for food choice of the fruitfly, *Drosophila melanogaster. Animal Behaviour, 36*, 106-114.

Wallin, A. (1994). *The Genetics of Foraging Behaviour: Artificial Selection for Food Choice of the Fruitfly, Drosophila melanogaster.* Licentiatavhandling, Göteborg: Göteborgs universitet.

Wallin, A. (1997). *Evolution: En undervisningssekvens i åk 8 - 9.* Opublicerad Examensuppgift i Na-didaktikkurserna I och II., Göteborg: Göteborgs Universitet, Institutionen för pedagogik och didaktik.

Wallin, A., & Andersson B. (2000). RenVarguppgiften Hemsidan tillgänglig [20031229] på http://na-serv.did.gu.se/evolution/ren1.html

Wallin, A., Hagman, M., & Olander, C. (2001a). Teaching and learning about the biological evolution: Conceptual understanding before, during and after teaching. In García-Rodeja Gayoso, I., Díaz de Bustamante, J., Harms, U., & Jiménez Aleixandre, M.P. *Proceedings from III Conference of European Researchers in Didactic of Biology (ERIDOB)* (pp. 127-139) Spain: Universidade de Santiago de Compostela.

Wallin, A., Hagman, M., & Olander, C. (2001b). Teaching and learning about the biological evolution: Comparing individual interviews and small group discussions for investigating students' conceptual understanding. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 2* (pp. 689-691). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Wallin, A., Sjöbeck, M.-L., & Wernersson, I. (2000). *Motivation och mening i naturorienterande undervisning. En intervjustudie med elever i grundskolans årskurs 8 och delvis 9.* (IPD-rapport 2000:06). Göteborg: Göteborgs Universitet, Institutionen för pedagogik och didaktik.

Verhoeff, R. P. (2003). *Towards systems thinking in cell biology education.* Doktorsavhandling, Utrecht: Universiteit Utrecht.

Viennot, l. (2001). Relating research in didactics and actual teaching practice: Impact and virtues of critical details. In Psillos, D., Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., & Kallery, M. (Eds.), *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 1* (pp. 22-26). Thessaloniki, Greece: Aristotle University of Thessaloniki.

Viennot, L., & Rainson, S. (1999). Design and evaluation of a research-based teaching sequence: The superposition of electric field. *International Journal of Science Education, 21*(1), 1-16.

Windahl, G. (2003). *Hjärnans roll vid inlärning?* Opublicerat föreläsnings manuskript. Föreläsning vid Göteborgs Universitet 2003-01-31.

Wolpert, L. (1992). *The unnatural nature of science*. London: Faber and faber.

Wood-Robinson, C. (1994). Young people's ideas about inheritance and evolution. *Studies in Science Education 24,* 29-47.

Vygotsky, L. (1986). *Thought and language*. London: The MIT Press.

Zetterqvist, A. (1995). De kan ju inte bara helt plötsligt börja växa – elever skriver om växters evolution. I Andersson, B. (Ed.) *Forskning om naturvetenskaplig undervisning. NA-SPEKTRUM nr 15* (pp 63-82). Mölndal: Göteboegs universitet, Institutionen för ämnesdidaktik.

Zetterqvist, A. (2003). *Ämnesdidaktisk kompetens i evolutionsbiologi. En intervjuundersökning med 26 no/biologilärare.* (Göteborg Studies in Educational Sciences 197), Göteborg: Acta Universitatis Gothoburgensis.

Zohar, A., & Ginossar, S. (1998). Lifting the taboo regarding teleology and anthropomorfism in biology education - heretical suggestions. *Science Education, 82*, 679-697.

Zook, D. (1995). Confronting the evolution education abyss. *Journal of Research in Science Teaching, 32*(10), 1111-1120.

Zuzovsky, R. (1994). Conceptualizing a teaching experience on the development of the idea of evolution: An epistemological approach to the education of science teachers. *Journal of Research in Science Teaching, 31*(5), 557-574.