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# **A Historical Approach to Children's Physics Education:**

*Modelling of DC-circuit Phenomena in a Small Group*

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ACADEMIC DISSERTATION

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## Abstract

This three-phase design research describes the modelling processes for DC-circuit phenomena. The first phase presents *an analysis of the development of the DC-circuit historical models* in the context of constructing Volta's pile at the turn of the 18<sup>th</sup> century. The second phase involves the *designing of a teaching experiment for comprehensive school third graders*. Among other considerations, the design work utilises the results of the first phase and research literature of pupils' mental models for DC-circuit phenomena. The third phase of the research was concerned with the *realisation of the planned teaching experiment*. The aim of this phase was to study the development of the external representations of DC-circuit phenomena in a small group of third graders.

The aim of the study has been to search for new ways to *guide pupils to learn* DC-circuit phenomena while emphasizing understanding at the qualitative level. Thus, electricity, which has been perceived as a difficult and abstract subject, could be learnt more comprehensively. Especially, the research of younger pupils' learning of electricity concepts has not been of great interest at the international level, although DC-circuit phenomena are also taught in the lower classes of comprehensive schools. The results of this study are important, because there has tended to be more teaching of natural sciences in the lower classes of comprehensive schools, and attempts are being made to develop this trend in Finland.

In the theoretical part of the research an *Experimental-centred representation* approach, which emphasises the role of experimentalism in the development of pupil's representations, is created. According to this approach learning at the qualitative level consists of empirical operations – like experimenting, observations, perception, and prequantification of nature phenomena, and modelling operations – like explaining and reasoning. Besides planning teaching, the new approach can be used as an analysis tool in describing both historical modelling and the development of pupils' representations.

In the first phase of the study, the research question was: *How did the historical models of DC-circuit phenomena develop in Volta's time?* The analysis uncovered three qualitative historical models associated with the historical concept formation process. The models include conceptions of the electric circuit as a scene in the DC-circuit phenomena, the comparative electric-current phenomenon as a cause of different observable effect phenomena, and the strength of the battery as a cause of the electric-current phenomenon. These models describe the concept formation process and its phases in Volta's time. The models are portrayed in the analysis using fragments of the models, where observation-based fragments and theoretical fragments are distinguished from each other. The results emphasise the significance of the qualitative concept formation and the meaning of language in the historical modelling of DC-circuit phenomena. For this reason these viewpoints are stressed in planning the teaching experiment in the second phase of the research. In addition, the design process utilised the experimentation behind the historical models of DC-circuit phenomena

In the third phase of the study the research question is as follows: *How will the small group's external representations of DC-circuit phenomena develop during the teaching experiment?* The main question is divided into the following two sub questions: *What kind*

*of talk exists in the small group's learning? What kinds of external representations for DC-circuit phenomena exist in the small group discourse during the teaching experiment?* The analysis revealed that the teaching experiment of the small group succeeded in its aim to activate talk in the small group. The designed connection cards proved especially successful in activating talk. The connection cards are cards that represent the components of the electric circuit. In the teaching experiment the pupils constructed different connections with the connection cards and discussed, what kinds of DC-circuit phenomena would take place in the corresponding real connections.

The talk of the small group was analysed by comparing two situations, firstly, when the small group discussed using connections made with the connection cards and secondly with the same connections using real components. According to the results the talk of the small group included more higher-order thinking when using the connection cards than with similar real components. In order to answer the second sub question concerning the small group's external representations that appeared in the talk during the teaching experiment; student talk was visualised by the fragment maps which incorporate the electric circuit, the electric current and the source voltage. The fragment maps represent the gradual development of the external representations of DC-circuit phenomena in the small group during the teaching experiment.

The results of the study challenge the results of previous research into the abstractness and difficulty of electricity concepts. According to this research, the external representations of DC-circuit phenomena clearly developed in the small group of third graders. Furthermore, the fragment maps uncover that although the theoretical explanations of DC-circuit phenomena, which have been obtained as results of typical mental model studies, remain undeveloped, learning at the qualitative level of understanding does take place.

**Key words:**

DC-circuit phenomena

small group learning

pupil talk

external representations of the pupils

connection cards

Experimental-centred representation

historical models of DC-circuit phenomena

teaching electricity in lower classes

## Tiivistelmä

Tutkimuksessa kuvataan tasavirtapiirin ilmiöiden mallinnusprosesseja kolmivaiheisessa kehittämistutkimuksessa. Ensimmäisessä vaiheessa *analysoidaan tasavirtapiirin historiallisten mallien kehittymistä* Voltan parin rakentamisen yhteydessä 1700- ja 1800-lukujen taitteessa. Toisessa vaiheessa *suunnitellaan peruskoulun kolmasluokkaisille opetuskokeilu*, jonka tekemisessä hyödynnetään muun muassa ensimmäisen vaiheen tuloksia sekä tutkimustietoa oppilaiden tasavirtapiirin mentaalimalleista. Tutkimuksen kolmas vaihe on suunnitellun *opetuskokeilun toteuttaminen*, jossa tutkitaan tasavirtapiirin ilmiöitä koskevien ulkoisten representaatioiden kehittymistä kolmasluokkalaisten pienryhmässä.

Tutkimuksen tavoitteena on ollut etsiä uusia tapoja *ohjata oppilasta oppimaan* tasavirtapiirin ilmiöitä kvalitatiivisen tason ymmärtämistä painottaen, jolloin vaikeaksi ja abstraktiksi koettua sähköoppia voisi oppia kokonaisvaltaisemmin. Erityisesti pienten koululaisten sähköopin oppimisen tutkiminen on jäänyt kansainvälisestäkin vähemmälle huomiolle, vaikka tasavirtapiirin ilmiöitä opetetaan myös alemmilla luokilla. Tutkimuksen tulokset ovat tärkeitä, koska peruskoulun alaluokkien luonnontieteiden opetusta on Suomessa vahvistettu ja pyritään kehittämään.

Tutkimuksen teoreettisessa osassa luodaan kokeellisuuden roolia oppilaan representaatioiden kehittämisessä korostava lähestymistapa, *kokeellisuuskeskeinen representaatioiden kehittyminen*. Lähestymistavan mukaan oppiminen kvalitatiivisella tasolla koostuu empiirisistä operaatioista – kuten kokeileminen, havaitseminen, hahmottaminen ja luonnonilmiöiden esikvantifiointi sekä mallintavista operaatioista – kuten selittäminen ja päättely. Opetuksen suunnittelun lisäksi uutta lähestymistapaa voidaan käyttää myös analyysivälineenä sekä historiallisen mallinnuksen että oppilaan representaatioiden kehittämisen kuvailussa.

Tutkimuksen ensimmäisen vaiheen tutkimuskysymyksenä on, *miten tasavirtapiirin historialliset mallit kehittyivät Voltan aikana*. Analyysin perusteella historiallisessa käsitteenmuodostusprosessissa erottuu kolme kvalitatiivista historiallista mallia, jotka sisältävät käsitykset suljetusta virtapiiristä tasavirtapiirin ilmiöiden tapahtumapaikkana, komparatiivisesta sähkövirtailmiöstä erilaisten havaittavien seurausilmiöiden syynä sekä pariston sähköisestä voimakkuudesta sähkövirtailmiön syynä. Nämä mallit kuvaavat Voltan aikaista tasavirtapiirin ilmiöiden käsitteenmuodostusprosessia ja -vaihetta. Mallit esitetään analyysissä käyttäen mallikehyksiä, joissa havaintoihin perustuvat fragmentit ja teoreettiset fragmentit erottuvat toisistaan. Tulokset korostavat kvalitatiivisen käsitteenmuodostuksen tärkeyttä sekä kielen merkitystä tasavirtailmiöiden historiallisessa mallintamisessa. Tästä syystä näitä näkökulmia painotetaan tutkimuksen toisen vaiheen opetuskokeilun suunnittelemisessa. Lisäksi tasavirtapiirin ilmiöiden opetuksen suunnittelussa hyödynnetään historiallisten mallien taustalla olevaa kokeellisuutta.

Tutkimuksen kolmannessa vaiheessa kysymyksenä on, *kuinka pienryhmän ulkoiset representaatiot tasavirtapiirin ilmiöistä kehittyvät opetuskokeilun aikana*. Kysymys jaetaan kahteen alakysymykseen: *Millaista puhetta pienryhmän puheessa ilmenee? Millaisia tasavirtapiirin ilmiöitä koskevia ulkoisia representaatioita pienryhmän puheessa ilmenee opetuskokeilun aikana?* Analyysissä havaitaan, että pienryhmän opetuskokeilu

onnistui tavoitteessaan aktivoida pienryhmän puhetta. Erityisen onnistuneeksi osoittautui opetuskokeilun suunnitteluvaiheessa kehitettyjen *kytkentäkorttien* käyttö puheen aktivoijana. Kytchentäkortit ovat virtapiirin komponentteja esittäviä kortteja, joiden avulla oppilaat tekivät erilaisia virtapiirikytkentöjä ja keskustelivat, millaisia ilmiöitä oikeilla välineillä tehdyissä vastaavissa kytkennöissä tapahtuisi.

Pienryhmän puhetta tutkitaan vertaamalla kahta tilannetta, joissa pienryhmä keskusteli samanlaisten – ensin kytkentäkorteilla, sitten oikeilla komponenteilla tehtyjen – kytkentöjen äärellä. Tuloksena oli, että kytkentäkortteja käytettäessä oppilaiden puheessa ilmeni enemmän korkeamman tason ajattelua sisältävää mallinnusta kuin vastaavassa keskustelussa oikeiden komponenttien kanssa. Vastauksena toiseen alakysymykseen analyysissa kuvataan pienryhmän puheessa opetuskokeilun aikana ilmenneitä ulkoisia representaatioita, jotka esitetään suljetun virtapiirin, sähkövirran ja lähdejännitteen fragmenttikarttojen avulla. Fragmenttikartat esittävät pienryhmän tasavirtapiirin ilmiöitä kuvaavien ulkoisten representaatioiden asteittaista kehittymistä opetus-kokeilun aikana.

Tutkimuksen tulokset haastavat aiemmat tutkimukset sähköopin käsitteiden abstraktiudesta ja vaikeudesta: kolmasluokkalaisten ulkoiset representaatiot kehittyvät selkeästi oppilaan puhetta ja aktiivisuutta korostavan pienryhmäopiskelun aikana. Lisäksi fragmenttikartat paljastavat, että vaikka tyypillisten sähköopin mentaalimallitutkimusten tuloksina saadut tasavirtapiirin ilmiöitä kuvaavat teoreettiset selitykset olisivatkin kehittymättömiä, oppimista tapahtuu tasavirtapiirin ilmiöiden kvalitatiivisen tason ymmärtämisessä.

**Avainsanat:**

tasavirtapiirin ilmiöt  
pienryhmäoppiminen  
oppilaan puhe  
oppilaiden ulkoiset representaatiot  
kytkentäkortit  
kokeellisuuskeskeinen representaatioiden kehittyminen  
tasavirtapiirin historialliset mallit  
alaluokkien sähköopin opetus

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# 1 Introduction

## 1.1 Purpose

The purpose of this research was to study comprehensive school pupils' learning processes of DC-circuit phenomena. The research was realised through a design research approach (Edelson 2002; Juuti and Lavonen 2006; Design-Based Research Collective 2003), in which ingredients for planning the teaching experiment were searched from the historical concept formation of DC-circuit phenomena. Recent results in the science education literature of learning electricity at school were also applied.

In the first phase of the study the historical concept formation processes of DC-circuit concepts analysed in their original context in the turn of the 18<sup>th</sup> century. A special turning point is Volta's discovery of the Pile, and the first battery experiments on the DC-circuit phenomena using it. On the basis of historical electric-current experiments and their interpretations, the modelling processes of DC-circuit phenomena were analysed. The second and third phases of the work aimed to plan a teaching experiment and study small groups of third and fifth graders in comprehensive school learning DC-circuit phenomena. The purpose was to track the development of models in small groups, the interest was both in subject matter learning of DC-circuit concepts, and in the learning process itself.

## 1.2 Rationale

This chapter will introduce both the 1) scientific and 2) politico-educational rationales, which were in the background of the study. The scientific rationale includes views of learning DC-circuit phenomena, and the challenges posed in learning this kind of abstract subject matter. The politico-educational rationale discusses learning of DC-circuit phenomena in light of the new national curriculum.

### 1.2.1 Scientific starting point: How are pupils guided to study DC-circuit phenomena?

A scientific standpoint of this study was an interest to uncover ways to guide pupils in their study of DC-circuit phenomena, which have been found to be difficult and abstract for pupils (Gunstone et al. 2009; Mulhall et al. 2001; Barbas and Psillos 1997). Many researchers, like McDermott and Shaffer (1992), Shipstone et al. (1988), Duit and Rhöneck (1997), Millar and King (1993), and Thacker et al. (1999) have reported that pupils of varying ages have problems in understanding DC-circuit concepts or working with electric circuits.

The learning problems typically occur in the qualitative stage of DC-circuit phenomena. Although pupils can solve quantitative exercises, they do not understand how

circuits function qualitatively nor can they apply the learned concepts to a concrete circuit. There exist many misconceptions of DC-circuit phenomena: it seems to be difficult for pupils to think the circuit as a whole instead of locally. Furthermore, the battery is often understood as a source of constant current, and the current is sometimes thought to run down in the circuit. The learning results of DC-circuit concepts tend to be weak and pupils' concrete observations of DC-circuit phenomena do not meet with their earlier conceptions of them. (McDermott and Shaffer 1992, 997; Duit and Rhöneck 1997) A special problem is primary school teachers' attitudes towards science subjects: many teachers find teaching science subjects difficult, this fact also has to be taken into consideration (Mulholland and Wallace 2000, 155; Appleton 2003).

How should the pupils be guided to study DC-circuit phenomena and the functioning of electric circuit? The first answer to the question is focusing on qualitative experiments instead of quantitative calculations. In McDermott's approach the starting point of learning DC-circuit phenomena is observation at the qualitative level. As a concrete example McDermott proposes that by comparing the relative brightness of bulbs in the electric circuit it is possible to connect the brightness with the relative strength of the current. (McDermott and Shaffer 1992; see also Hämäläinen et al. 2000; Arons 1997, 194-200) According to McDermott (1997) studies' direct experiences with simple circuits can promote learning by helping them to construct conceptual models of DC-circuit phenomena.

The second way to deal with the question posed is to apply different teaching and learning approaches, which increase pupils' possibilities to talk more in the learning situation. The small group's positive effect on learning is emphasised in the science education literature (Bennet et al. 2004; Cobb and Yackel 1996; Huber 2003; for more see in chapter 4.3.2). The learning process of a small group is central to the research in this study. Teaching approaches, which take into consideration the historical concept formation processes of a subject matter also seem to be promising (for more see chapter 3.3.4).

This study focuses on young students, and the learning of DC-circuit phenomena of this group has not been studied in Finland or elsewhere to any great extent. The target group, 9-11-year-olds, has not been of special interest at the international level either (Georghiades 2000, 121-122). Science learning studies have generally concerned pupils of the upper level of comprehensive school, or older students. Also in the domain of DC-circuit phenomena, studies of learning difficulties have centred on pupils who have already finished the lower level of the comprehensive school. For example Cosgrove et al.'s (1985, 249) study examined 10 – 18-year-olds' external representations of DC-circuit phenomena, in Shipstone's study (1984, 75) 12–17-year-olds, in Borges and Gilbert's study (1999, 101) the age group was from 15 -year-olds to adults, in the study of Psillos et al. (1987) 14–15-year-olds, and Tsai et al. (2007) 13–16-year-olds. Tiberghien's (1983) and Lee's (2007) studies are exceptions; in Tiberghien's study pupils in the age group 8-year-olds onwards, and in Lee's study 10–11-year-olds were scrutinised. Finnish studies of learning electricity have focused on older students (e.g. Hirvonen and Saarelainen 2000; Karhunen, Koponen and Kallunki 2003).



### **1.2.2 A national education policy as a starting point: National curriculum reform**

The other starting point to this study has been politico-educational, namely the national curriculum reform in Finnish comprehensive school (FRAME 2004). The new curriculum has made some important changes in science subjects at the lower level of the comprehensive school, i.e., grades 1 to 6. According to the Finnish National Framework Curriculum pupils will start to learn a new subject called “Physics and Chemistry” in grade five. Furthermore, the curriculum clearly specifies much of the physics subject matter in environmental and natural studies for grades 1 to 4.

FRAME gives a description of a good performance at the end of the fourth grade. According to these criteria, the students’ know-how of DC-circuit phenomena should be as follows: the pupil will know how to connect up a simple electrical circuit using a battery, lamp, and wires. Furthermore, the pupil is required to achieve the following general abilities: 1) know how to make observations with the different senses and how to direct their attention towards the essential features of the object of those observations, 2) know how to describe, compare, and classify objects, organisms and phenomena on the basis of their various properties, 3) know how, with guidance, to carry out simple investigations of nature, natural phenomena, and the built environment, 4) know how to express – orally, in writing, and by drawing – the information they have acquired about nature and the built environment. (FRAME 2004)

After the sixth grade of comprehensive school, the pupil’s knowledge about DC-circuit phenomena should be extended as follows: know about different voltage supplies, such as a battery and an accumulator, and know how to do experiments in which electricity is used to produce light, heat and motion. She/he should also know that electric current and heat can be generated from various natural resources. The thinking and experimenting skills attained are presupposed to achieve the following level: 1) know how to make observations and measurements with different senses and measuring instruments, and how to direct their observation at the target's essential features, such as motion or temperature, and at changes in those features, 2) know how to draw conclusions from their observations and measurements; to present their measurement results with the aid of tables, for example; and to explain causal relationships associated with fundamental natural phenomena and the properties of objects - for example, the greater the mass a body has, the more difficult it is to put it into motion or stop it, 3) know how to perform simple experiments, for example to investigate what factors affect the dissolving of a solid, 4) know how to use concepts, quantities, and their units in describing, comparing, and classifying the properties of substances, objects, and phenomena, and 5) know how to assemble the information they have found in different sources, and to weigh its correctness on the basis of their prior knowledge, their investigations, and discussions with others. (FRAME 2004)

So, the new curriculum brings a big change to physics instruction at the lower levels of comprehensive school. Particularly, the study of DC-circuit phenomena has also been given a clear target for the lower grades. The subject matter, which was previously taught casually in the technical work lessons have now become a fixed part of the curriculum. As

the situation is new, there exist no earlier traditions for teaching DC-circuit phenomena to all pupils. From the standpoint of science education research it will be interesting to see, what kinds of learning results are achieved and how the new subject matter could be taught.

As can be seen from the quotations above, the goals of learning science, and particularly DC-circuit phenomena are quite high. The nature study skills that are required presuppose a qualitative understanding of DC-circuit concepts. If the pupil can interpret her observations, make conclusions and compare the observed phenomena, she would understand quite many of the concepts of electric circuit at the qualitative level. The knowledge content at grades 1-4 mostly embrace the concept of an electric circuit, but if the above-mentioned nature study skills are applied, the qualitative understanding of the concepts of electric current and voltage will also be included. In grades 5-6 the instruction defines the parts of an electric circuit by focusing on of the functions of a battery. The connection between energy and electric current is also specified. However, the curriculum does not give any specific methods for realising the proposed instruction. The exact meaning of a simple electric circuit is not defined, neither is the level of the required learning results in the field of conceptual understanding. However, as discussed above in section 1.2.1, particularly, a qualitative understanding of the DC-circuit phenomena has proved to be the most difficult aspect of learning the subject matter. Thus, the goals of the new FRAME are set at a high level.

In this study, a politico-educational starting point, i.e., the goals of learning DC-circuit phenomena in grades 1-6, will be used as part of a needs assessment for designing the teaching experiment in phase 3 of this study (see section 6.1).

### 1.3 Research questions

The subject of this study, *A Historical Approach to Children's Physics Education: Modelling of DC-circuit phenomena in a Small Group* reveals the main research purposes. The aim is to connect two separate processes of the same phenomena, namely the historical view to the knowledge creation process and pupils' learning process of DC-circuit phenomena (see chapter 6). Thus, the focus of the research is on the processes of learning.

In the first phase of the study the stress is on analysing the historical concept formation of the DC-circuit phenomena. The concept formation processes will be approached from the standpoint of developing models and the experiments behind them, so the first research question is:

*1. How did the historical models of DC-circuit phenomena develop in Volta's time?*

The second research question concerns the learning process of the small group during the realisation of the teaching experiment. As mentioned in section 1.2.1, one important starting point for this study has been a problem of "how to guide pupils to learn". On the basis of theoretical knowledge of small group's positive impact on learning the solution of the teaching experiment is to try to find a solution to the problem in this way. Thus the second research question will examine the modelling processes of a small group:

*2. How will the small group's external representations of DC-circuit phenomena develop during the teaching experiment?*

The processes of learning will be analysed in two phases, so the main question is divided into the following two sub questions:

*2.1 What kind of talk exists in the small group's learning?*

*2.2 What kinds of external representations for DC-circuit phenomena exist in the small group discourse during the teaching experiment?*

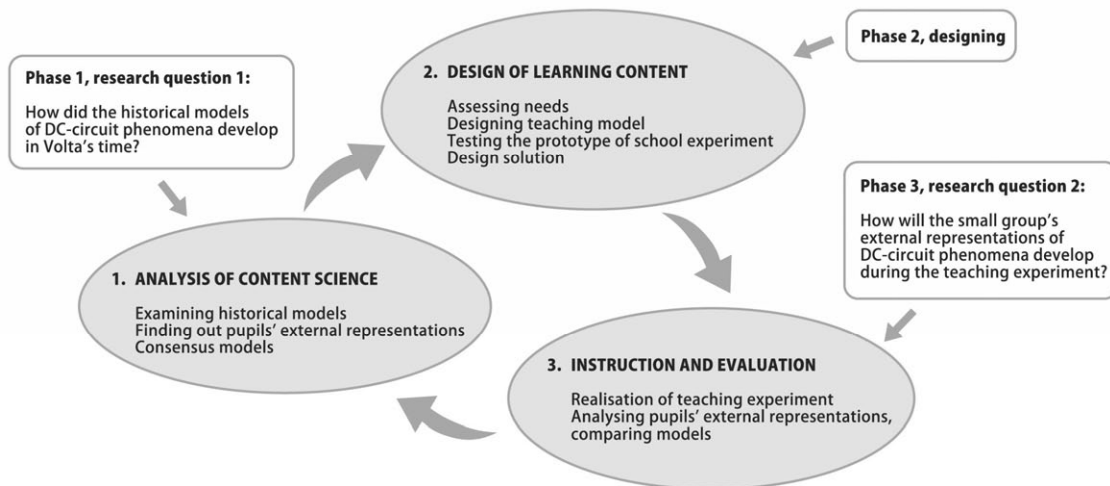
See also Figure 1. The research questions that have been set, are also supported by the following background assessments:

1. Knowledge of the historical concept formation process and historical models can help in planning the teaching of DC-circuit phenomena.
2. Qualitative experiments and variations of the situation offer a rich learning environment.
3. Learning is more effective in a small group because of the possibility to talk.

## **1.4 The cycle of design research in this study**

This study belongs to the wide design oriented research tradition, and has mainly been influenced by the design-based research paradigm (Design-Based Research Collective 2003) and the model of educational reconstruction (Duit 2006). The study consists of three sequential phases, which form a cycle of research. (See sections 4.2.1 and 4.2.2 for a detailed description of the research method).

This study contains the following three phases: 1) Analysis of content science, 2) Design of learning content, and 3) Instruction and evaluation. The proportional connections of the research questions to these different phases are shown in Figure 1. Phases have a close feedback to one another, which is characteristic of the design research. The first phase of the study includes parts of analysing the historical models of DC-circuit phenomena. There are also reports of common pupils' representations for DC-circuit phenomena in the science education literature. In the second phase of the study, the teaching model of DC-circuit phenomena is designed and the prototype of the teaching experiment on the grounds of the found historical models and corresponding pupils' representations of DC-circuit phenomena is developed. The last phase of the study includes the actual realisation of the teaching experiment, and analysis of pupils' external representations (For more see section 4.2.2).



**Figure 1** *A picture of the design-research cycle of the study. Phase 1, research question 1; phase 2, designing; phase 3, research question 2.*

## 1.5 The structure of the research report

This research report contains nine chapters. The first chapter (Introduction) describes the purpose and rationale, the research questions, and introduces research design and the historical approach. Furthermore, the chapter includes the structure of the research report and a definition of terms.

The main learning theories at the background of the study are presented in chapters 2 and 3. Chapter 2 sets up the social learning environment designed in the second phase of the study. For this purpose the social constructivist approach and the different roles of language in learning and doing physics are discussed. In chapter 3, a new approach of learning physics, the Experimental-centred representation approach, is designed based on the empirically orientated perceptual approach and more theoretically orientated model-based reasoning. In practice uniting the two approaches involves building an analysis tool for the content analyses of the study, which will be used for analyses in phases 1 and 3, as well as a tool for designing the teaching experiment in phase 2.

Chapter 4 discusses methodological issues. Pragmatism as a research paradigm and qualitatively orientated research are introduced. Moreover, the chapter includes a detailed description of research design traditions and realising this study as a design research. Also concrete data gathering and analysing methods are depicted. Small group learning is described as a special feature of data gathering and learning.

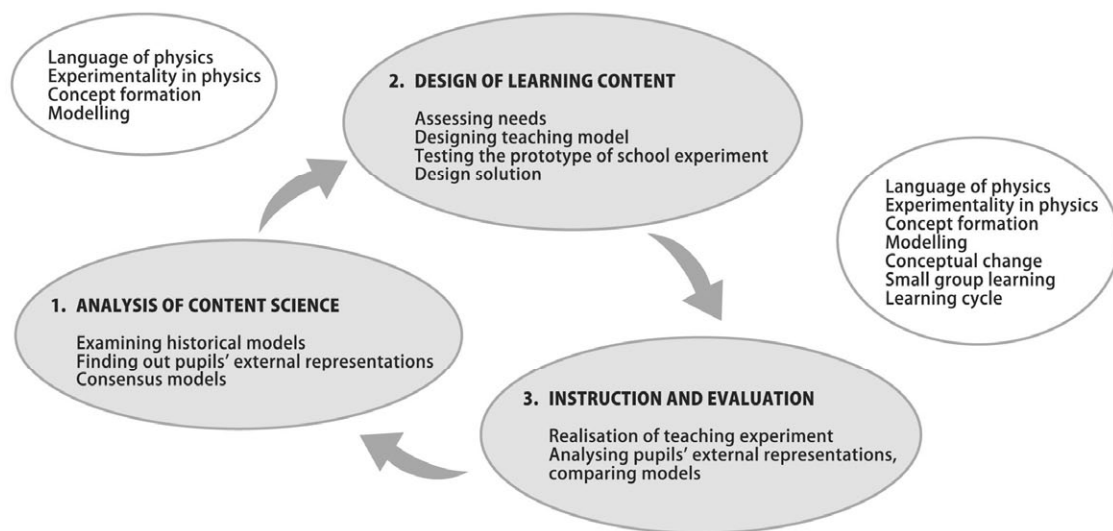
Chapter 5 presents the development of historical models of DC-circuit phenomena, the results to the first research question after phase 1 of the study. The models and empirical basis of closed circuit, electric fluid and contact electricity are depicted as a result of content analysis. Chapter 6 describes the second phase of the study explaining and depicting the process of planning the teaching experiment. Different aspects, which affect

the design solution are discussed, and as a result subject matter -, pedagogical and structural outcomes are portrayed.

Chapter 7 gives answers to the second research question based on the content analysis of the teaching experiment data. The results consist of descriptions of levels of talk in a small group, the reasoning involved in using the designed connection cards in connections, and development of small group’s external representations of the electric circuit, the electric current and the source voltage.

Chapter 8 discusses trustworthiness in the research. Chapter 9 presents a summary of the results, a comparison between the analysed small group’s external representations and earlier reported pupils’ representations of DC-circuit phenomena, a comparison between the analysed small group’s external representations and historical models of DC-circuit phenomena. Furthermore, the summary discusses the advantages of the research in science education research and to the practical school teaching of DC-circuit phenomena. Finally the implications for further research are discussed.

Figure 2 shows the phases of the study (1-3) and the corresponding theoretical frame of reference. The figure is a modification of the original Figure 1 for design research cycle, which was presented above. As can be seen from the figure below, the theoretical aspects used in exploring historical concept formation in DC-circuit phenomena (phase 1) and in realisation of the teaching experiment (phase 3) have a lot of similarities – language, experimentality, concept formation, and modelling – appear in both steps. The theoretical similarity reflects the purpose of the study: by paralleling the processes of doing and learning science, it is possible to examine the modelling processes of DC-circuit phenomena from two standpoints (see section 1.3 of the research questions).



**Figure 2** *Theoretical backgrounds used in different parts of the study.*

## 1.6 Historical approach in physics learning

The historical approach in learning physics, which has been applied as a part of this design research, is quite a new branch of teaching. The traditional way of using the history of physics is to include in schoolbooks of physics extra information about inventions or earlier important researchers, but the new historical approach means much more. In recent years the history of science has been used as a source of new perspectives to promote science learning. The historical processes of constructing knowledge have been paralleled to the learning processes in science (e.g. Nersessian 2002b; Justi and Gilbert 2002; Matthews 1994; Gauld 1991). So, one aim of utilising the history of science in physics learning is to highlight the processual structure of concept formation (Galili and Hazan 2000; Nersessian 1995).

One way of implementing the historical approach is to replicate the original experiments using modern instructions (Binnie 2001), and this way to perceive the conceptual progress in the domain. A more profound way is to incorporate historical models to experimental course of physics (Galili and Hazan 2000; see also Justi 2000; Justi and Gilbert 2000). In this kind of research the historical models i.e. the conceptual evolution of human thought are paralleled to the pupils' own external representations of the domain. In the International Pendulum Project the historical approach means applying the original experiments of pendulum motion. The focus is on the key features of scientific method and important aspects of the interplay between science and its social and cultural context (Matthews et al. 2004). Spiliotopoulou-Papantoniou's (2007) and Dedes' (2005) studies advocate a basic research, which concentrates on comparing the processes of historical concept formation and learning at school. See chapter 3.3.4 for more.

In this study, the historical approach has two different aspects. Firstly, from the purely scientific viewpoint it is interesting to parallel and compare the found similarities in processes of historical modelling and learning (phases 1 and 2 of the study). Secondly, the information of historical models, and in their background existing concept formation processes including original experiments, are utilised as a source of inspiration for planning the teaching experiment of DC-circuit phenomena (phase 3).

## 1.7 Definition of terms

To establish a common understanding and a vocabulary for this research, the main physics terms used in the research report are defined. The historical concepts will be used in chapter 5 while describing the development of historical models of DC-circuit phenomena. Otherwise, the present modern concepts are used. The classification of concepts has been done on the grounds of classes of gestalts (entities, phenomena, and properties) and their quantitative representations (quantities), see sections 3.2.1 and 3.2.2.

**Table 1** *Definition of terms. See sections 5.5 and 6.4.*

<b>Category of concept</b>	<b>Historical concepts</b>	<b>Present concepts</b>
entity	<i>closed circuit</i>	<i>(electric) circuit</i>
entity	<i>electric fluid</i>	
phenomenon	<i>flow of the electric fluid</i> <i>current of the electric fluid</i> <i>electric current</i>	<i>electric current / electric-current phenomenon</i>
property of phenomenon	<i>strength of electric current</i>	<i>current strength</i>
quantity		<i>electric current</i>
entity	<i>the Pile</i>	<i>chemical pair</i>
property of entity	<i>power of putting in motion of electric fluid</i> <i>electric power/ strength of the electric power</i> <i>electromotive force of the pair</i>	
phenomenon		<i>current-source phenomenon</i>
property of phenomenon and entity		<i>magnitude of the current-generating property / strength of the electric source</i>
quantity		<i>electromotive force / source voltage</i>
phenomena		<i>DC-circuit phenomena (includes all electric-current phenomena in the electric circuit)</i>
phenomenon		<i>direct current</i>
phenomenon		<i>static electricity</i>

## **2 Social learning and language**

In this study the learning of physics takes place in a social context, in a small group, by talking and discussing. To set up the learning environment designed in the second phase of the study (see section 6.6), different aspects relating to the social situation will be discussed in this chapter. Firstly, the social constructivist approach will be described in section 2.1. After that the different roles of language of physics relating to its meaning as a social tool in learning will be described in section 2.2.

### **2.1 From personal constructivist to social constructivist approaches**

Recent science education research has adopted views of social constructivist and sociocultural perspectives to complete personal constructivist approaches of learning. The aim has been to enlarge our view of the complex process of learning. (Duit and Treagust 2003, 672; Anderson 2007, 18-20; Scott et al. 2007, 48)

The different perspectives of learning can be organised into two dimensions: 1) metaphors of acquisition and participation see learning as gaining or participation processes (Sfard 1998, 5-6), in proportion, learning can be reviewed from the view points of 2) individual or social processes. According to Scott et al. (2007) cognitive or personal constructivist approaches like conceptual change see science learning as involving a process of acquisition and focus on the individual as a learner. Cognitive approaches are found in the work of Piaget. On the contrary, the Vygotskian perspective of learning highlights learning as acquisition, which takes place in a social context. According to Vygotsky (1978, 57) learning takes place first in social situations like discussions and lately becomes internalised on the individual plane. Using the work of Vygotsky as a basis, the so-called social constructivist views of learning, have been developed. These share the following insights into learning: 1) learning scientific knowledge takes place from the social to personal planes, 2) the learning process includes individual sense-making, 3) learning is mediated by semiotic resources like language, and 4) learning science involves learning the social language of the scientific community. (Scott et al. 2007, 35-38, 41, 44).

Cobb and Yackel determine social constructivist (emergent perspective) as a combination of an individual's activity emphasising psychological constructivist and collective oriented social interactionist view, in which case the standpoints of individual's and group's meaning of the concept formation are combined. This means taking into account both an individual's own and the active learning process, and the group's interior discussion and negotiation of the meanings of concepts (Cobb and Yackel 1996, 176-177; McClain and Cobb 2001, 105).

As mentioned above, social constructivism has its roots in the work of Vygotsky and his followers. According to this school of thought learning is a process of learning the social language of science (Scott et al. 2007, 42). From this viewpoint, for example a



small group's talk and language are the focus of learning, because they create meanings for the matter to be learnt. Vygotsky's salient concept, the zone of proximal development (ZPD) (see section 2.2.2) includes an idea of learning as a social process, when it highlights the role of the mediation of a small group or a teacher (Shayer 2003, 471-472). Cobb and Bauersfeld (Cobb and Bauersfeld 1995, 9-10) claim that it is not possible to differentiate an individual's from the action of a small group. From this perspective Kaartinen and Kumpulainen (2002, 191) attach to know-how in sociocultural framework the terms; belonging, participating and communicating, whereas in cognitive oriented approaches knowing means having knowledge.

In this study (phase 3) the focus is mainly on the social constructivist perspective, because the small group's learning will be studied through the talk and discussions in the group, and the language used will be analysed. However, the ultimate target of the analysis is to chart the developing processes of the small groups' external representations of the DC-circuit phenomena. This purpose fixes the focus to the conceptual development of DC-circuit phenomena taking place in a small group, where pupils learn by sharing the ideas of science under the guidance of the teacher (see also Appleton 2007, 512).

In the first phase of the study, while analysing the historical concept formation processes, we are also aware of the social aspect of doing science, but the main focus is however on the individual's knowledge of the construction process.

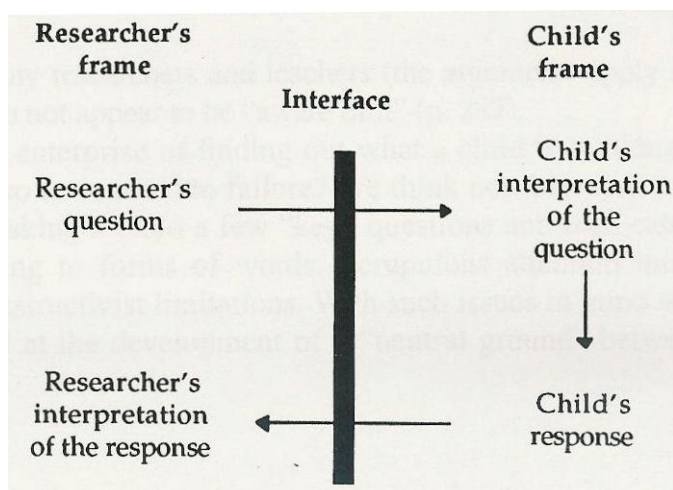
## **2.2 The language of physics**

### **2.2.1 Physics – a foreign language**

Language is our tool to communicate with each other (Mercer 2000). Without language we cannot tell others our thoughts and ideas. Every language has its own grammar and special words by which we can try to express ourselves. Our knowledge of language can be weak, so it is more difficult to put into words exactly what is in our minds. For children grammar difficulties also create intangibles, and things they can only partially understand. Furthermore, languages have lots of different metaphors, which generate their own contributions to the interpretation.

Learning physics can be understood as starting to learn a new foreign language. Like any other languages, physics has difficult words and a special grammar (see e.g. Brookes and Etkina 2007). That is why beginner's language cannot be so fluent like experts. Arons and Kurki-Suonios underline the role of the physics teacher to give pupils the opportunity to use physics language and to act as role models in using the language correctly (Arons 1997, 57; Kurki-Suonio and Kurki-Suonio 1994, 170). Pupil's own speech, i.e., speaking about the subject in their own words is seen to be especially important. According to Lemke (1990) learning means skills to use linguistic tools like concepts and models. Also Mercer (2000, 14) emphasises on a general level that language, as a tool needs a social context to be developed.

According to Johnson and Gott understanding a child's thinking in a physics lesson is not a simple task (Johnson and Gott 1996, 563). The language the child uses must be approached from the standpoint of her/his existing cognitive, "frame of reference". This means that the child can use only the words she/he knows, only the "grammar" of physics she/he knows. These kinds of language problems result in difficulties in any dialog between a child and an adult. For example in a typical interview there can be at least two misunderstandings if 1) the child doesn't understand the researcher's question and if 2) the researcher can't interpret the answer. (See Figure 3.)



**Figure 3** *Translation interface: Johnson and Gott use the concept "translation interface" to explain possible cases for misunderstandings in a dialog between a researcher and a child. The arrow rightward indicates a child's possible misunderstanding, and respectively the left pointing arrow indicates a researcher's misapprehension. (Johnson and Gott 1996, 564)*

In this study the aim of the researcher and the teacher is to avoid too scientific definition-like talk, and instead to try to talk in an observation-orientated way in order to connect better the children's way of thinking. On the grounds of numerous learning studies (more in section 4.3.2), a small group is an effective learning environment. Small group learning activates children to negotiate, think together and to talk with their own words. It can be supposed that other children can better understand their peer group's talk. It might also be easier to interpret children's talk if they explain their conceptions to each other.

### 2.2.2 Raising the level of pupils' language and thinking

In this section the focus is on the level of pupils' language and thinking. Firstly, the section describes Vygotsky's idea of raising the level of thinking by learning with others rather than independently. Secondly, a tool for examining pupils' thinking skills is introduced. Both categories of cognitive processes and levels of argumentation are shown

to be possible tools for analysing the levels of pupils' language and thinking. Thirdly, the section also includes a discussion of the effect of pupil's age on the level of thinking. In this discussion Piagetian stages of thinking are applied.

*"The only 'good learning' is that which is ahead of development." (Vygotsky 1978, 89)*

Vygotsky represented thoughts as supporting the interaction between child and teacher, and so promoting learning. According to him pupil's learning can be supported at the so-called zone of proximal development (ZPD), which means "the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" (Vygotsky 1978, 86). Thus the idea is to raise pupil's stage or area of mental activity with the aid of a teacher or peer group. In this way pupils can solve problems, which are a little bit too difficult for them to solve alone. As said by Vygotsky, the ZPD has a more important role in learning than the level of actual development, thus learning should be directed to the ZPD. (Vygotski 1982, 184) The idea of a ZPD fits to the thoughts of Bodrova and Leon, who have also emphasised the meaning of language and thinking together: according to them it is important for a child to get a possibility to compare his/her mental structures both with that of an adult and in a peer group (Bodrova and Leong 1996, 4).

The emphasis of learning at the background of the ZPD is in social interaction. In this process language is in the central role, so that at first language is used in social interaction and afterwards it becomes a tool of thinking as well. Thus, thinking can be understood as an inner speech as distinct from speech in social interaction. The role of language is to support thinking, and this way it can be said that meanings are born in communication. According to Vygotsky conceptual thinking does not begin until an awkward age. (Vygotski 1982, 18-19, 96, 148-149) Therefore, social interaction is a possible way to improve children's learning. By forming peer groups and activating children's speech and interaction learning is possible to quicken the learning process. For more see section 4.3.2.

### *Higher-order thinking*

The level of pupil's thinking can be examined using the conceptions of educational objectives of Bloom's taxonomy and higher-order thinking forms. Bloom's taxonomy is an educational tool to assess learning and plan instruction. The revised taxonomy classifies different educational objectives of a pupil into two hierarchical dimensions, 1) knowledge and 2) the cognitive process. The knowledge dimension includes categories of factual knowledge, conceptual knowledge, procedural knowledge and meta-cognitive knowledge. To the cognitive process dimension belong categories of remembering, understanding, applying, analysing, evaluating, and creating. The categories of the two dimensions classify educational objectives from the lowest to the highest levels. Thus the aim is to help teachers' to assess learning according to the two dimensions, and plan instruction to support higher learning results. (Anderson and Krathwohl 2001, 67-68)

**Table 2** *The cognitive process dimension according to Anderson and Krathwohl (2001, 67-68).*

Categories of cognitive processes	Alternative names	Thinking level
6. Create – put elements together to form a coherent or functional whole; reorganize elements into a new pattern or structure		higher-order thinking skills
Generating	Hypothesizing	
Planning	Designing	
Producing	Constructing	
5. Evaluate – make judgements based on criteria and standards		
Checking	Coordinating, detecting, monitoring, testing	
Critiquing	Judging	
4. Analyze – break material into its constituent parts and determine how the parts relate to one another and to an overall structure or purpose		higher-order thinking skills
Differentiating	Discriminating, distinguishing, focusing, selecting	
Organizing	Finding coherence, integrating, outlining, parsing, structuring	
Attributing	Deconstructing	
3. Apply- carry out or use a procedure in a given situation		
Executing	Carrying out	
Implementing	Using	
2. Understand – construct meaning from instructional messages, including oral, written, and graphic communication		higher-order thinking skills
Interpreting	Clarifying, paraphrasing, representing, translating	
Exemplifying	Illustrating, instantiating	
Classifying	Categorizing, subsuming	
Summarizing	Abstracting, generalizing	
Inferring	Concluding, extrapolating, interpolating, predicting	
Comparing	Contrasting, mapping, matching	
Explaining	Constructing models (e.g. cause-and-effect models)	
1. Remember – retrieve relevant knowledge from long-term memory		
Recognizing	Identifying	lower-order thinking skills
Recalling	Retrieve	

According to Zohar and Dori (2003, 147) the categories of cognitive processes in Bloom's taxonomy can be classified into the higher- and lower-order thinking skills. The category of understanding is used as a landmark for the classes: remembering belongs to the lower-order thinking skills, whereas categories beyond understanding i.e. applying, analysing, evaluating, and creating are enumerated as higher-order thinking skills. In this study, however, the category of understanding is also classified as a higher-order thinking skill. This resolution is justified by the age of the pupils participating in the research. Most of the 9-year-olds as well as 11-year-olds are still on the level of concrete operations (see Figure 4), thus it is plausible that attaining the category of understanding and especially its

highest sub-category, explaining, really evidences higher-order thinking. Furthermore, the sub-category explaining is the first category including model-constructing, which obviously requires higher-order thinking (see more about model-constructing in section 3.3). In this study the categories of cognitive processes are applied in ordering levels of pupils talk in the context of research question 2, see section 7.2.

### *Argumentation*

Alongside research into cognitive processes (higher-order thinking skills) there has been developed research into argumentation (Erduran and Jimenez-Aleixandre 2008) in science education research. Argumentation is understood as an instrumental tool in learning and doing science that helps to build explanations, models and theories. (Siegel 1995; Erduran et al. 2004, 916-917). The sociocultural perspectives of cognition have been used as the theoretical background of argumentation and it is fundamentally based on Vygotsky's theories of learning in a social context (Erduran et al. 2004, 917).

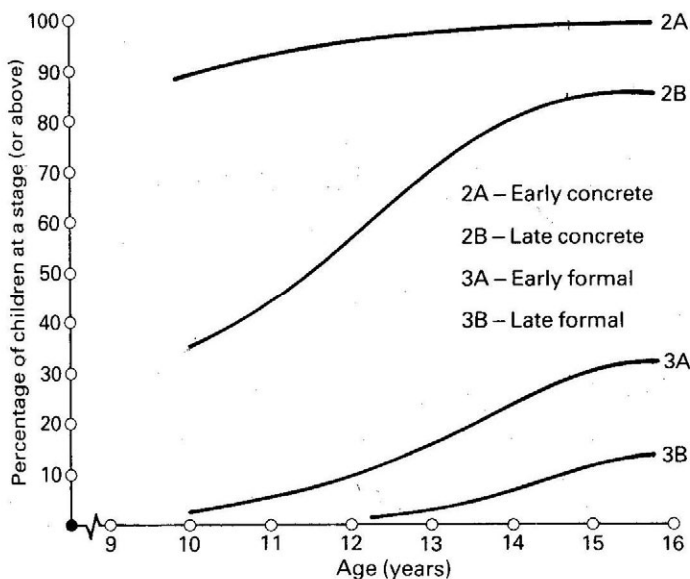
The research of argumentation is founded on Toulmin's Argument Pattern (Toulmin 1958), where the structure of an argument includes a claim, data, a warrant, backing, and a rebuttal. The meaning of the data is to support the claim; warrants provide links between the data and the claim; backings strengthen the warrants; and rebuttals point to the circumstances, where the claim is not true (Erduran et al. 2004, 918). In Erduran et al's (2004) research the aim was to study how the quality of argumentation discourse would progress during the intervention. In the research the quality of small group's argumentation was measured by the nature of rebuttals; the more and stronger rebuttals the higher the level of argumentation. The lowest (1) level of argumentation consists of arguments that are a simple claim versus a counter-claim or a claim versus a claim; whereas the highest (5) level of argumentation displays an extended argument with more than one rebuttal (Erduran et al. 2004, 921, 928).

Erduran et al's (2004) levels of argumentation come close to the Anderson and Krathwohl's (2001) categories of cognitive processes introduced in Table 2. Especially the higher-order thinking skills surely require skills of argumentation as well. However, the perspective of this study is slightly different; the purpose of research question 2.1 is to uncover possible higher-order thinking skills in order to analyse small group's cognitive modelling processes (external representations). Thus, for the purpose of content analysis, categories of cognitive processes offer a wider frame of analysis. On the other hand, argumentation fits well with small-group learning (see section 4.3.2 and 6.6; see also Bennet et al. 2004, 9), and so argumentation also plays an important role in small-group learning in this study.

On the other hand, as it will be discussed in chapter 5, at the background of the historical models of DC-circuit phenomena was Volta's and Galvani's debate on the nature of electricity. This argumentation is a good example of using arguments as tools of modelling.

*From concrete operations to formal operations*

From the standpoint of developmental psychology child's thinking is understood to develop from the so-called concrete operational level of thinking to formal operations. As depicted by Piaget younger pupils (age 7-11) think at the stage of concrete operations. This stage is characterised by the use of logic, and includes the following processes: 1) Decentering – taking into account multiple aspects of a problem. 2) Reversibility – an ability to understand changing and returning numbers or objects. 3) Conservation – understanding that the quantity of matter will be conserved although the stages of its changes. 4) Serialisation – an ability to arrange objects in order. 5) Classification – an ability to classify objects. 6) Elimination of Egocentrism - the ability to view things from another's perspective. The biggest deficiency in thinking skills children have at the stage of concrete operations is the inability to understand abstract problems. At the stage of formal operations thinking has clearly achieved the level of logicity and abstract. It is also possible to draw conclusions from the information available, and understand matters theoretically. (Shayer and Adey 1981, 4, 9) Figure 4 below shows the Piagetian stages and proportions of children of different ages.



**Figure 4** *Proportion of children at different Piagetian stages at different ages. (Shayer and Adey 1981)*

In this study pupils are 9-11-year-olds meaning that the oldest of them are just transferring to the stage of early formal operations, so it is plausible that abstract subject matter such as DC-circuit phenomena are difficult for them to learn. However, age is not the only factor affecting to child's thinking and learning. As will later be discussed in section 6.2, instruction also has an important role in developing a child's thinking. Relating to the topic of this study Borges and Gilbert (1999) have reported that most scientific models of DC-circuit phenomena also require instruction and experimenting for them to be developed.

### 2.2.3 Formation of the language of classical physics

Language as a carrier of meanings is an important view to this discussion of the language of meanings. According to MacKinnon the language of classical physics can be realised as a linguistic parasite, which attaches to ordinary languages and effects mutations (MacKinnon 2002), so the perspective in which to consider the language of physics is philosophical. Its foci are classical physics and especially conversations between experts. MacKinnon also asserts that the language used in doing science should be studied because its role is so salient in clarification problems during conceptual revolutions and in objectivity in physics in general (MacKinnon 2002, 2, 26). However, the role of language in physics has traditionally been considered as secondary, only to act as a “semi-transparent medium” between a researcher and reality. According to MacKinnon things are not nonetheless so simple; classical physics is a language of discourse, discussion between experts forms the language of physics.

According to MacKinnon the language of classical physics has formed and changed under the effects of social and historical dimensions. This changing can be reviewed from a point of view of a conceptual core, which includes different classes of concepts used in the language. The conceptual core has changed and impacted the language written and spoken in classical physics. The origin of the conceptual core is in classification. Like any other language, also physics has a categorisation as a basic feature. In physics the first categories are from Aristotle. His basic categorisation included classes of substance, quantity and quality. In addition, to enable comparison between qualities, the idea of the intensification and remission of qualities was introduced. This progression developed the conceptuality of the language of physics and made it possible to discuss measurement. This meant a new concept, the quantity of a quality (MacKinnon 2002, 2-3, 7-8). According to MacKinnon in Galileo’s time the categoral system of physics developed by distinction between the real properties of bodies. Galileo introduced concepts of shape, size, location, motion and contacts. Qualities were also specified. Measuring became more important so that only measurable quantities were understood as real. The end of eighteenth century was a real period of quantities and measuring. The development of experimental devices and measuring emphasised the role of quantities and uncovered new phenomena in physics. (MacKinnon 2002, 10) In this way, the formation of the language of classical physics set up the structure of concept formation, which is discussed in detail in section 3.2.

The development of the language of classical physics can also be studied from the standpoint of linguistic transitions between different branches of physics. These transitions have often happened from mechanics to other branches. For example atomism and energy were this kind of extending concepts, by which were explained thermodynamics, and in the case of energy thermodynamics, optics and electricity. Moreover, attempts were made to explain Baconian physics like electricity in mechanistic way by asking, “how fast does it move” or “whether it is a substance” (MacKinnon 2002, 11, 14; cf. analogical modelling in section 3.3.1).

## 2.2.4 Language in school physics

Physics learning can be considered as learning the social language of school physics (Bakhtin 1934/1981, 430; Vygotsky 1934/1987) or school scientific language (Izquierdo-Aymerich and Adúriz-Bravo 2003, 40).

This language offers learners thinking and talking tools (cf. section 2.1). According to Mortimer and Scott (2003, 13), in pupils' talk we can differentiate between everyday and scientific social languages (see also Duit and Rhöneck 1997; Duit et al. 1985, 205-214; Arons 1997, 18). Everyday social language is pupils' day-to-day communication with other people, and it includes informal or spontaneous concepts, which are also called alternative conceptions or misconceptions (for more see chapter 3.3.2) The term, scientific social language, refers to language used and learnt in the classroom, or in real science.

Mercer (2000, 4-) has taken note of general linguistic misunderstandings in conversations. The same words can either be misunderstood or understood in a different way in a form, which was not intended. From the standpoints of thinking and creativity it is even fruitful that words can carry different meanings. Conversely, if thought from the viewpoint of school physics and a pupil, the use of an originally physical concept like energy can enlarge in ordinary language so much that its original meaning is blurred (Kurki-Suonio and Kurki-Suonio 1994, 275). Clerk and Rutherford have also discussed language from the standpoint of misunderstanding. According to them especially scientific words, whose meanings differ from their everyday meanings, can lead to misconceptions. Moreover, the language used in physics textbooks can be too difficult or complicated to understand (Clerk and Rutherford 2000, 706-707).

Yore et al. have examined oral interactions at school science lessons, and they conclude that the quantity and quality of these interactions seem to be low. According to them, increasing the variety of language tasks might positively affect the understanding of science. For example oral discourse in laboratories, in classroom instruction and small group discussion should be used to achieve better learning results. Moreover, Yore et al. propose that the language processes scientists use, might also have some application possibilities in promoting science learning. (Yore et al. 2003, 689, 691, 697) Other proponents for using language as much as possible in school lessons are Myhil et al. (2006, 7) with their conception of the meaning of talk in learning. Myhil et al. emphasise that the role of talk is not only a product of learning activities, but also an important process in supporting learning.



### 3 Empirical concept formation and modelling

In this chapter learning of physics will be discussed from the two different standpoints: 1) empirical concept formation and 2) modelling. The chapter begins with a discussion of different conceptions of the role of experimentality in physics and physics teaching 3.1. Thereafter, section 3.2 introduces the first approach of learning applied in this study, the perceptual approach, which offers a very concrete picture of empirical concept formation in physics learning. Later in section 3.3, the second approach of learning applied in this study, the model-based reasoning will be introduced. Chapters 3.4 and 3.5 introduce the new approach of learning physics, the Experimental-centred representation, which has been designed on the grounds of the above mentioned perceptual approach and model-based reasoning approach. This new approach will be used as a tool of analysis in analysing 1) the development of historical models of DC-circuit phenomena and 2) the development of small groups' external representations of DC-circuit phenomena during the teaching experiment. The approach will also be utilised in planning the teaching experiment in the second phase of the study.

#### 3.1 Experimentality in physics and physics teaching

The role of experimentality in physics is undisputable. *Physics is an experimental natural science*, this is one of the often-heard definitions of the discipline. Historically experimentality has played an essential role in the concept formation processes in the different fields of physics, but there exists also a close dialectics between experimentality and theory in concept formation. However, it is not possible to unambiguously definite the role of physics' experimentality in relation to theory. The views of the relation have varied a lot in the philosophy of science. In the history of physics this relation between experimentality and theory has also changed. The different roles of experimentality in physics can be reviewed among others from the standpoints of science history, the philosophy of science, doing physics, or learning school physics.

According to Franklin (2009; 1999), who discusses the subject from the standpoints of the history and philosophy of science, the roles of experiment in science can be listed as follows: 1) to confirm a theory by testing it and thus providing the basis for scientific knowledge, 2) to refute an accepted theory, and call for a new theory, 3) to provide hints to the mathematical structure of a theory, 4) to have a life of its own, independent of theory. A single experiment also can have several of these roles.

Hacking emphasises the meaning of measuring methods and experimental devices in the progress of science (Hacking 1983, 56-57). The progress in this field also means development in experimentality. MacKinnon mentions the end of the eighteenth century as an example, when the new experimental devices of electricity, magnetism, chemistry, or early thermodynamics first time enabled quantitative results (MacKinnon 2002, 10; cf. also section 2.2.3). The first phase of this study focuses on the history of DC-circuit phenomena. The results of this phase will prove the crucial role of the experiments in the

concept formation process of electricity (see chapter 5). Thus, the history of electricity at the end of 18<sup>th</sup> century and at the beginning of 19<sup>th</sup> century is a good example of an era of a strong impact of experimentality on concept formation. On the other hand, at the beginning of 20<sup>th</sup> century, the blossoming of quantum mechanics is a different kind of example of a strong era of theory.

There also exist views that mix the roles of experimentality and theory in doing science. For instance Weisskopf, one of the biggest quantum theorists of the 20<sup>th</sup> century and a long-time leader of CERN, has described physics research as a voyage of discovery (Saarikko 2006; Gottfried 2002, 396). This kind of picture of physics includes a strong intuitive element and a very flexible relation between experimentality and theory.

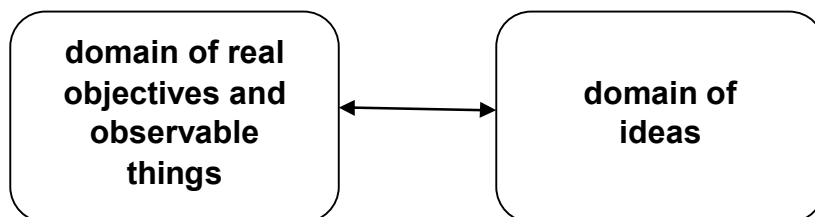
From the viewpoint of science education, the role of experimentality diverges from its role in science. The baseline to learn physics at school is generally the role of a beginner, which differs from a scientist's role. That is why the main aims of science education to develop 1) students' scientific knowledge, and their 2) knowledge about science, define the experimentality in physics lessons somewhat different than in science (Millar 2004, 2). The second aim, knowledge about science, includes the purpose to increase students' knowledge of doing science, like its methods etc. In developing students' scientific knowledge Millar refers to Piaget's theses that constructing representations of the external world (learning) needs acting and reflecting. This means that experimentality generally comes before theories in physics lesson. The first aim of experiments is to enable students to "identify objects and phenomena and become familiar with them". After this Miller lists their aims as to learn facts, concepts, relationships and theories or models. (Millar 2004, 6-7, 9)

From the personal constructivist point of view, experimentality is an essential part of pupil's active knowledge's constructing process. Trumper emphasises the role of experimentality in the spirit of personal constructivism: It is hard to imagine learning to do science, or learning about science, without doing laboratory or fieldwork (Trumper 2003, 645). He also states that the purpose of experimental work, which is done in laboratories, is to offer to students opportunities to think about, discuss, and solve real problems (Trumper 2003, 654).

Lavonen and Meisalo (2006) list four distinctive factors in experimentality which are different in teaching and science. The first thing is that the standard and aims are higher in science. Secondly, in science experimentality means really gaining new knowledge, whereas the purpose of teaching is pupil's learning, or constructing new knowledge and developing new skills. Thirdly, experimentality has an important role in motivating the learner and developing her/his personality. Fourthly, the aim of experimentality in teaching is also to prove the nature of science as an experimental science.

For a pupil, learning physics means adopting a new language (see section 2.2.1), and she/he is not at the same thinking level of development as researchers. Furthermore, in learning physics the connection between theory and experimentality – ideas and real objects and events – is not a matter-of-course for a pupil. That is why Millar highlights the role of experimentality to make links between the two domains of knowledge. (Millar 2004, 8, 18) The domain of real objects and observable things, which is a part of pupil's everyday experience, and the domain of ideas that includes the knowledge structure of a

pupil, are connected with experimentality, see Figure 5. On the other hand, physicists also deal with the same domains of knowledge, but at a much more higher level.



**Figure 5** *The role of practical work: connecting the two domains of knowledge (Millar 2004, 8.)*

The connection between experimentality and theory in empirical concept formation, which will be described in section 3.2, is a very important part of the process. The role of experimentality is essential as a starting point of conceptualisation, however the other side of the cycle, theory is also a necessary part of the process. The interaction between experimentality and theory is especially important so that these parts of concept formation complete each other: while experimentality aims to represent the natural phenomena the aim of theory is to explain them (Kurki-Suonio and Kurki-Suonio 1994, 145, 150).

### **3.2 The perceptual approach – an approach of empirical concept formation**

The perceptual approach (Kurki-Suonio and Kurki-Suonio 1994) is an empirical based approach of learning physics, which also interfaces with the philosophy of science. This approach highlights the empirical origin of concepts, and their construction on the grounds sensory experiences. According to the approach concepts develop gradually, so that the language used has an essential role in the process. The approach emphasises an active role for the pupil in concept formation, so it can be classified in the field of personal constructivism.

According to the perceptual approach the construction of the meanings of concepts starts necessarily from the level of perception, by sensory experiences. Experimentality at this level creates the basis for concepts, which then acts as a foundation for all subsequent interpretations of empirical knowledge obtained at more quantitative levels of empirical exploration. In the beginning, the mental constructions, which can be thought of as ordering elements or pictures, are kinds of 'gestalts'. (Kurki-Suonio and Kurki-Suonio 1994, 145-146, 158-68; see also Arons 1997)

Gestalts thus defined have a very similar role as the experiential gestalts introduced by Lakoff and Johnson (Lakoff and Johnson 1980) and Anderson (Anderson 1986), and the explanatory gestalts introduced as complementary structures to experiential gestalts by Watts (Watts 1996). As the conceptions belonging to the so-called alternative thinking,

alternative frameworks and 'children's science' (Pfund and Duit 1994) (see section 3.3.2), these gestalts are also based on direct sensory experiences, on everyday experiences and on intuition. Whereas alternative thinking is particular and situation dependent, gestalts are broader and general patterns used to explain and understand experienced wide-ranging phenomena.

A given gestalt is composed of several elements, and is more than the sum of its parts. One example is a gestalt of causation, which consists of a notion of an agent, an object, a cause and an effect (Anderson 1986). Similarly, the explanatory gestalt of essence is constructed on the basis of things 'taken for granted' or which are taken to be 'natural', although there is no direct sensory experience (Watts 1996). The importance of initial organizing mental constructions as a starting point for learning has also been recognized by diSessa (diSessa 1993, 111-114), who also argues for the formation of stable, spontaneously created cognitive constructions called p-prims, which are fundamental and self-explanatory patterns.

Gestalts acquire their meanings from perceptions, and a concept can be taken to represent something that has already been understood as a gestalt on the level of perception (Kurki-Suonio and Kurki-Suonio 1994, 146). The concept formation, which starts from nature phenomena is a process directed from phenomena to theories. The concept formation takes place in cycles, which consist of alternating stages of representation of observed phenomena and interpretation based on the current conceptual scheme. Representation is guided by the seeking of structures through generalizations and these structures are justified by using inductive reasoning. Interpretation means understanding existing reality starting from the principles at the conceptual level, on the level of theory. Predictions concerning specific situations are inferred from general principles by using deductive reasoning. Inductive and deductive 'half-cycles' are both part of the whole process, but the possibility to imagine that induction or deduction separately could be used as a route to learning should be rejected (Kurki-Suonio and Kurki-Suonio 1994, 148-149).

Paying attention to concepts only as a product of the cycle is, however, not yet sufficient. This would reduce the scientific process concept formation to a mechanistic induction-deduction cycle and display the concept as a logical and unavoidable outcome of this process. Concept formation is never tied to logical necessity; instead, an intuitive component is always a part of it (Kurki-Suonio and Kurki-Suonio 1994, 150-151). This is also behind the network view (Duhem 1991; Quine 1975; Nersessian 1984), and the logical empiricist point of view, expressed e.g. by Einstein in form "The concepts and propositions get "meaning" viz. "content" only through their connection with sense experiences. The connection of the latter with the former is purely intuitive, not itself of a logical nature" (Einstein 1949, 13). The scientific process, including learning, can therefore be regarded rather as an intuitive than a logical process, although logic also has a central role in this process. Concepts are processes, (Kurki-Suonio and Kurki-Suonio 1994, 266), a notion that is of utmost importance for learning and teaching, and which shifts the attention from factual, definitional knowledge to functional and processual aspects of knowledge.

The concept, a gestalt, comes close to the concept, a mental model, which will be described in section 3.3. Both gestalts and mental models are depicted as developing mental constructions, which form the bases for pupil's concepts. However, the view of the two close concepts is to some extent different. The gestalt concept highlights the ideal steps of empirical concept formation on the qualitative level from the standpoint of knowledge structure, whereas modelling is based on a more theoretical oriented conception of learning. In this study both approaches of learning are utilised (for more see section 3.4).

### **3.2.1 Perception: foundation of the network**

According to the perceptual approach (Kurki-Suonio and Kurki-Suonio 1994, 158) the concept formation process cannot be separated from the formation of the network of concepts, the structure of theory. Logical structurization has a central role in the formation of the structure. However, not only quantities, but also general laws have their origins in sensory experiences and perception, and essentially the same processes are present on the levels of qualitative and quantitative knowledge. The following phases can be discerned in concept formation: qualitative knowledge – quantification – structurization. In the following, the stages in the interest of this study, which belong to the level of qualitative knowledge, perception and prequantification, are discussed in detail.

Language is an essential tool in every level of concept formation. Its role is especially emphasised in the very beginning, in the phase of perception. In this phase are laid the foundation for correctly understanding basic concepts by creating ways of talking about the phenomena observed. (Kurki-Suonio and Kurki-Suonio 1994, 170-171; see also section 2.2.4) Perception is the process, which starts concept formation on the level of qualitative knowledge and builds the basic gestalts by recognition and classification of entities and phenomena and their relationships. In this building process the meaning of a developing concept is first created (Kurki-Suonio and Kurki-Suonio 1994, 264-265) through experimentalism in the form of sensory experiences, observation and qualitative experiments. Arons has also highlighted the same principle: according to him the idea first, name afterward principle describes the thinking and reasoning process of physics (Arons 1997, 195; Hake 2004, 6, 10).

A class of gestalts consists of entities (objects), phenomena and their properties (qualities). Among the gestalts formed at the stage of perception we also find more general gestalts, like gestalts of causation (compare with Anderson and Lakoff) and conservation.

The gestalts formed in perception lay the foundation for the conceptualisation. Already at this level of qualitative knowledge, the comparative operations of properties, as diminishing, increasing etc. are possible and they add meaning to the initial gestalts. These comparative operations are precursors of the more quantitative operations and therefore they can be called prequantification.

### **3.2.2 Prequantification**

According to the perceptual approach prequantification is a phase of concept formation, which precedes quantification. Prequantification develops the qualitative dependences and concepts, which form a foundation and a motive for quantification. The background of prequantification is in perception. Thus the meaning, and the goal of prequantification, is to modify the entirely qualitative knowledge of different gestalts to the form of comparative knowledge. This means that the situation of an experiment has to be varied (Kurki-Suonio and Kurki-Suonio 1994, 163) by comparing whether the property of an entity or a phenomenon, that is the gestalt, which has been identified on qualitative perception, can be changed or varied. If there are noticed different strengths of the property, the next step is to do experiments in a restricted situation. It is studied how the property of the entity or the phenomenon alters if the situation is changed.

So the gestalts, which were started to perceive in the perception stage do get more exact forms on prequantification and progress to comparative concepts. The final aim of the prequantification – and the whole qualitative concept formation – is to find a qualitative empirical law, the first gestalt of quantitative law representing the invariance of the new property, and to show that there exists a motive to quantify this new property (Kurki-Suonio and Kurki-Suonio 1994, 183, 264-65; see also Koponen 2007, 13). In this phase intuition has an essential role. The use of intuition connects mental pictures to phenomena.

In this study, both in the analyses of historical models and the small group's external representations of DC-circuit phenomena, the focus is on the qualitative level of concept formation. Thus, the phases of qualitative concept formation described here will be used as parts of the new approach of learning, which will later be used as a tool of analysis. As it will be depicted in sections 3.4 and 3.5, the new approach adopts fragments of observation and perception, understanding causal relations, forming of gestalts, doing prequantitative experiments, and finding concepts and empirical laws between them to the new approach.

### **3.3 Models and modelling – ways of representation**

Many philosophers and cognitive psychologists are at the background of models and modelling in learning and teaching. For instance Gilbert et al. (2000b, 27-34) name Kuhn, Bunge and Nersessian as researchers that have developed the idea of modelling. According to Koponen (2007) modelling is based on the Semantic View of Theories, and originates from works by Suppes, van Fraassen and Giere. Just recently, Nersessian (2008, 8, 19) has mentioned Craik as the original psychologist and physiologist of modelling.

The field of modelling and model-based learning and teaching is wide and growing. However, the basic concept, the mental model, is still undefined and it has many different conceptions. According to Nersessian, there exists however a general hypothesis that mental representations are organised in units, which include knowledge of spatio-temporal

structure, causal connections and other relational structures. (Nersessian 2008, 9-10; Franco et al. 1999, 290)

The three tasks of science education – to help pupil 1) to learn sciences 2) to learn about science, the history of science and methodology, and 3) to learn to do science – can also be understood from the viewpoint of modelling. Modelling is an important way of achieving these goals, because the formation of mental models is central to any learning processes. Also in doing experimental tests of models, pupils are doing something very typical to scientific research. (Hodson 1993; Gilbert et al. 2000a, 13)

In this study a new approach for understanding learning processes in physics is developed on the grounds of the perceptual approach (section 3.2) and the model-based reasoning (MBR) (see section 3.3.1). The new approach offers a comprehensive conception of learning processes of science, deepening the unspecified picture of model-based reasoning of concept formation, and describing modelling as a key factor in the progress of learning. The new approach will be presented in section 3.4.

### **3.3.1 Model-based reasoning**

The model-based reasoning (MBR) is an approach of learning, which describes both scientist's and pupil's concept formation processes highlighting modelling as a part of the learning process. In the model-based reasoning, the focus is on the process – in a similar way as in the perceptual approach – instead of learning results. According to Nersessian (1999) modelling is a fundamental form of human reasoning, a kind of “think-aloud” reasoning process. Thus the new structure of knowledge develops as an outcome of a reasoned process, which is not accordant with a traditional account of reasoning. From the point of view of MBR, conceptual changes are considered as extended problem-solving processes. (Nersessian 1999, 6, 13-14)

Nersessian (1999) differentiates between three specific forms of model-based reasoning defining them as productive methods of conceptual change. The forms are 1) analogical, 2) visual or 3) simulative modelling. In analogical modelling the generative principles and constraints for a new model are sought from a source domain. The modelling happens by using generic abstraction to recognise potential similarities between disparate domains (See also Harre 1970; cf. section 2.2.3 linguistic transitions). The second way of modelling is to construct visual representations of the phenomenon. Visual representations make it possible to model the conceptual structure if the linguistic or other expedients are too limiting. External visual representations can be used to support people's inner modelling processes. Model-based reasoning can also be simulative modelling, which means peoples' ability to simulate physical situations in their minds. A specific form of simulation is thought experimenting, which is based on narrative presentation of a real phenomenon. Another advantage in the case of thought experimenting is the ability to withdraw from the limits of the physical situation, and to link the conceptual and the experimental dimensions of human cognitive processing (See also Reiner 2000). By thought experimenting it is possible to make demonstrations that would have undesirable consequences in the real world. (Nersessian, 1999, 6, 15-21; Nersessian 1995, 207)

Alongside the imagistic form of modelling described above, there has also been proposed that modelling takes place in language-like operations. This kind of representations are understood to refer to physical objects, structures, processes, or events. As a special feature of linguistic representations is its relationship to truth, which means that these kinds of representations are understood to be true or false. According to Nersessian, linguistic modelling requires a grammar that specifies the proper syntactical structures. (Nersessian 2002a, 135; Nersessian 2008, 14-15)

In this study the focus is on written historical data and pupils talk in a small group, and the language used is highlighted. In analysis of historical and empirical data the forms of language will be reviewed from the perspective of developing representations. Thus, the study emphasises the linguistic modelling forms. However, at least simulative modelling is also used during the teaching experiment to underpin the small group's thinking processes. An example of this type of modelling is the use of connection cards, by which real connections can be simulated (for more see section 6.6.1).

### 3.3.2 Model categories

Extending modelling as a basic form of reasoning to the all areas of learning, teaching or doing physics or other natural sciences generates a need to review the features more closely:

In fact, doing science is just constructing models. ... Physics and models are not found at the ready in nature, but physics means constructing and improving models. ... The student has a certain model of reality. This often differs from the "official" model of physics. The task of the teacher is to persuade the student to use the physicist's model.

*Viiri 1996, 84*

As quoted above, the models students and physicists have differ from each other, and the role of teacher is to help students to acquire a more scientific model. What are then the student's models, and the "official" model? According to Gilbert et al. (Gilbert, Justi and Ferreira 2007; Gilbert et al. 2000a, 12; Gilbert and Boulter 1998, 56, 60; Justi and Gilbert 2002, 370) different models can be classified on the grounds of their ontological status:

1. An internal representation<sup>1</sup> (or a mental model) of a pupil is an individual's private and personal cognitive representation, which is formed either on her own or within a group<sup>2</sup>. By internal representation pupils make models mentally available to themselves.

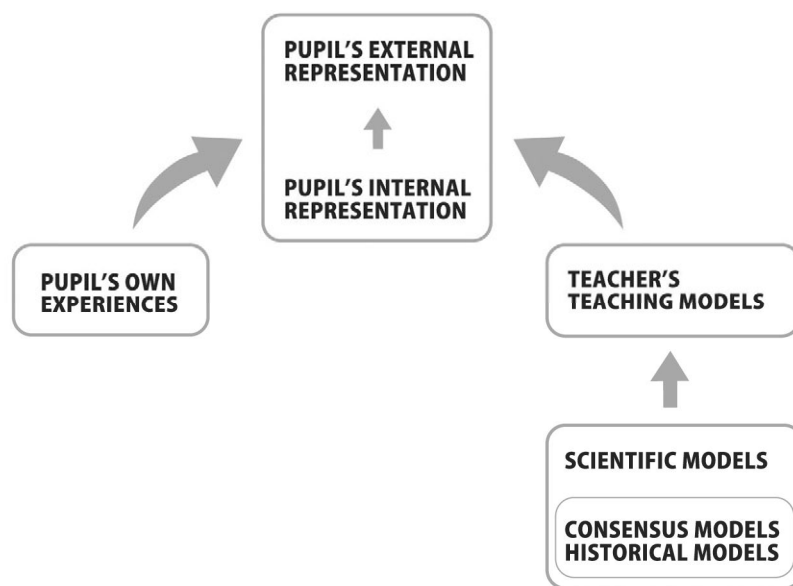
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<sup>1</sup> The term "internal representation" instead of "mental model" has been used recently to describe better pupil's tentative phase of modelling. In proportion the use of "external representation" has become general.

<sup>2</sup> Mental models cannot be directly accessed, only inferred from the major modes of human communication: gesture, speech, and writing (Justi and Gilbert 2000, 994).



2. An external representation or an expressed model of a pupil is a mental model, which an individual tells to someone, writes etc. Briefly, an external representation makes a model available to others. It is believed that expressing it changes the mental model.
3. A consensus model is formed in a social group, after discussion and experimentation. As in the case of expressed mental models, published consensus models become scientific models. These scientific models represent existing scientific conception of a phenomenon. Older consensus models, which have been produced in specific historical context and superseded, are called historical models.
4. Teaching models are particularly in classroom situations planned models aiming to help understanding consensus, historical or curricular models.



**Figure 6** *Relations between different models. Pupil's external representations and internal representations are based on her/his own experiences and on the teacher's teaching models. Teachers construct their models on the basis of the consensus model. Older consensus models are called historical models.*

#### *Pupil's external representations*

As mentioned above the old concept of mental model has recently been replaced by pupil's internal representation (Gilbert et al. 2007), which describes better the nature of the tentativeness of these models. When discussing pupil's modelling process, the new term will be used in this study instead of mental model, but the latter will be maintained in its original references. Because internal representations are private and internal, they can only be studied indirectly, through external representations (cf. Skopeliti and Vosniadou 2007). In this study the focus is on pupil's external representations, which an individual makes available to others, thus all of these pupils' views relating to their qualitative understanding are referred to by the term external representation.

The term “mental models” has quite a long history. For example Johnson-Laird (1983), Gentner and Gentner (1983), Bobrow (1985), Vosniadou and Brewer (1992) and Tiberghien (1994) have discussed them earlier, and also nowadays they are at the focus of much science education literature. Nersessian enumerates some examples of a vast body of research, which actually examines mental models. To these domains belong for example qualitative reasoning, reasoning of causality in physical systems, representations of intuitive domain knowledge in various areas, the role of representation in reasoning, deductive and inductive reasoning, and discourse and narrative understanding. Moreover she refers to her own area of interest, problem-solving practices. (Nersessian 2008, 11; Nersessian 2002b, 139; Nersessian 1995; see also Jonassen 1995)

In the science education literature, models are generally connected to the formation of knowledge in the mind of a researcher, a teacher or a student. We mean by the term model, “a representation of an idea, object, event, process, or system”. (Gilbert et al. 2007; Gilbert et al. 2000a, vii) Nersessian claims that models are especially “mental representations with which a scientist carries out much reasoning and by means of which she thinks and understands through the lens of a conceptual structure” (Nersessian 1999, 15). In addition, mental models are defined as a “form of knowledge organization” (Nersessian 2002b, 140). From the point of science education models are a part of pupils’ learning processes, and they help them to structure the learned content in relation to earlier conceptions. Meanwhile, in scientific research the purpose of any model is to simplify a phenomenon and to explain it (Gilbert et al. 2000a, 11).

According to Nersessian, mental models can be either structures in long-term memory or temporary structures created in working memory during comprehension and reasoning processes. The first mentioned mental models are in the form of qualitative models and are can be used flexibly in many reasoning tasks. The second form of mental modelling happens during narrative and discourse comprehension for example in creative reasoning. What is especially interesting for this study, is that these kinds of mental models are thought to change during the discourse. (Nersessian 2002b, 140-141)

Franco and Colinvaux have proposed that the features, which make mental models of concern to research, are their generative (to produce predictions and new ideas) and synthetic (to consist of a simplified representation) nature, their tacit knowledge (to involve subconscious aspects), and their limited scope (to limit the range of models, which could be built) (Franco and Colinvaux 2000, 100-101). Moreover Redish (1994) lists both positive and negative aspects of mental models: 1) They include information in the form of propositions, images, rules and statements. 2) The information can include incongruousness and be incomplete. 3) Despite the rules of procedures, people cannot use them. Furthermore, Carley and Palmquist (1992) attach mental models to the language of science: mental models are linguistically mediated, i.e. the language of science is a very important tool in understanding them. (cf. section 2.2)

Besides mental models, within science education research there is a wide variety of concepts describing pupils’ views, beliefs and conceptions, which relate to their qualitative understanding. These conceptions represent the development of the social language of school physics (see section 2.2.4). Among others, misconceptions (Rowell et al. 1990; Black 2006; Chi et al. 1994; McDermott 1999; Chi and Roscoe 2002; Driver et

al. 1985), alternative conceptions (Rowlands et al. 1999), student's conceptions (Duit 1993), p-prims (diSessa 1993), facets (Hunt and Mistrell 1994, 52-53), and schemas (Sabella 1999; Bao and Redish (2001) can be paralleled to this family of concepts, and they all have similarities with pupils' mental models.

### *Consensus models and teaching models*

As portrayed in Figure 6, teaching models are usually constructed on the basis of generally accepted consensus models, which represent the scientific conception of a given nature phenomenon. According to Hart (2008) consensus models have also been used as teaching models as such. Examples of consensus models of DC-circuit phenomena are current conservation and Ohm's law. However, in the case of electric circuits, the consensus models are considered to be on a too abstract level, so special teaching models have had to be developed; like the electron-transport model, the rope model, and the water-flow model. Hart criticises teaching by consensus models without taking the modelling process into account. Moreover, she refers to the wide criticism of the absence of models, which provide a complete and coherent picture of the DC-circuit phenomena. (Hart 2008, 529-532)

There has also been proposed a set of criteria for a good teaching model. According to the criteria, a good model is initially intelligible to pupils, the model's causal mechanisms are meaningful and make it possible to think about the model in own terms, it allows articulating and addressing common conceptual difficulties and misconceptions, it engages the pupils' imagination and intellect and promotes a rich classroom discourse, it enables pupils to move towards the relevant consensus models of science, and it is overtly presented. (Hart 2008, 534-535) From the standpoint of this work the criteria presented fit well to the approach of learning adopted. However, as will be discussed in section 3.4, the approach of learning in this study mixes the views of the perceptual approach and model-based reasoning, so the teaching model is wider including elements of experimentality and modelling. Thus, the purpose of this study is not to offer pupils ready models as thinking tools, but to arrange a talk- and think-activating small group environment (section 6.6), where learning of DC-circuit phenomena takes place through developing external representations of the small group. So, the purpose is to support the pupils' own modelling processes instead of offering a ready made model.

The relations between the models enumerated in Gilbert et al.'s categorisation are shown in Figure 6, which focuses on pupil's modelling. From the perspective of the pupils, the factors affecting their external representations are their previous experiences (like their own experiments), from teaching appearing teaching model, and finally behind teaching model affecting scientific models. In the figure above, historical models have also been placed with the factors behind teaching. This placing is based on recent research, which has compared and applied the historical models in learning physics (for more see section 3.3.4).

As discussed in Figure 1, this research applies all the models from different categories. In the first phase of study the focus is on historical models and pupil's external representations of DC-circuit phenomena, which are also compared to the scientific consensus models of the subject matter. In the following phase (2) the emphasis is on

teaching models, whereas the last phase (3) concentrates again on pupil's external representations.

In this study pupils' external representations are taken into consideration at several stages: to begin with, in the context of the first phase of the study when comparing historical models of DC-circuit phenomena with pupils' common external representations (according to the science educational research) of the subject matter (see section 6.2). The next times utilising the knowledge of external representations takes place is in designing the teaching model (section 6.5), and then in realisation of the teaching experiment (section 6.7). This time the external representations of the small group are uncovered in preliminary, intermediate and final interviews. Besides, the focus of the whole study is in the modelling processes (cf. section 1.3 of research questions), so the design artefact, the teaching experiment, is planned as much as possible from the view of thinking-aloud to uncover pupils' and the small group's developing external representations (see section 6.6).

### **3.3.3 Operationalising external representations**

According to Jonassen (1995) mental models can be explored as learning outcomes. Because mental models tend to have a quite abstract and intangible nature, a more accurate analysis of them requires operationalising. Jonassen's idea is to formulate and concretise the representations of mental models and then assess the changes that happen during the learning processes. A variety of methods can be used in this assessment. Another approach of operationalising models is the typology of expressed models, of Boulter and Buckley (2000, 57).

For operationalising mental models a different kind of knowledge has to be collected. To uncover epistemic models, which are not known to others or not necessarily understood by the knower, the models have to be expressed in one way or another. Thus Jonassen's mental models in fact are akin to expressed models, which in this study are called pupils' external representations (cf. model categories in section 3.3.2). Jonassen (Sasse 1991) proposes methods like using think-aloud, problem solving, the user's explanations and predictions of systems (cf. Nersessian 1999 in section 3.3.1).

The following forms of knowledge are collected in Jonassen's study: 1) Structural knowledge, which is the knowledge of the structure of concepts in a domain. These kinds of data can be expressed for example by concept maps. 2) Performance/Procedural Knowledge means knowledge, which is brought out with troubleshooting a simulated task, thinking aloud and articulating. 3) Reflective procedural knowledge appears in teaching-back procedures while learners teach each other. The representations can be for example verbal descriptions or visual illustrations. 4) Imaging a system means producing verbal or visual representations of mental models. 5) Metaphors are an individual's way to search for similarities between new and existing knowledge. They can be found by asking learners to explain their way of thinking. 6) By executive knowledge we mean the learner's ability to apply necessary cognitive resources to various applications. (Jonassen 1995)

As discussed in section 3.3.1 Nersessian lists three imagistic forms of modelling – analogical, visual and simulative modelling – and the linguistic representing. These forms can be classified on the basis of Nersessian’s modelling forms. In the following table (Table 3) Jonassen’s criteria (characteristic) for evaluating pupil’s external representations on the basis of multiple data sources (measure) are presented, and the corresponding forms of modelling are sorted in the third column. Boulter and Buckley have also made the same kind of classification of the models (2000, 53).

From the point of this study, the main omission in Nersessian’s and Jonassen’s classification of modelling is the absence or underemphasizing of experimenting as a crucial form in the modelling process. And this is the most important reason for mixing the two approaches in this study (see section 3.4). According to the approach of learning adopted in this study, pupils’ own experiences of experimenting and making their own observations are essential parts of learning (see section 3.4), thus in this study the forms of modelling described in Table 3 are completed with a strong emphasis on experimenting.

**Table 3** *Criteria for assessing pupil’s external representations on the grounds of multiple data sources. The table is a mixture of Jonassen’s and Nersessian’s ideas; the characteristics and measures are from Jonassen (1995) and forms of modelling from Nersessian (Nersessian 1999, 6, 15-21; Nersessian 2008, 14-15).*

<b>Characteristic</b>	<b>Measure</b>	<b>Form of modelling</b>
Coherence	Structural knowledge, Think-aloud	Visual, Linguistic
Purpose/Personal Relevance	Self-report, Cognitive interview	Analogical, Visual, Linguistic
Integration	Cognitive simulation	Simulative
Fidelity with the Real World	Comparison to expert	Analogical, Visual, Simulative, Linguistic
Imagery	Generating metaphors, analogies	Analogical
Complexity	Structural knowledge	Visual
Applicability/Transferability	Teach back, think aloud	Analogical, Visual, Simulative
Inferential/Implicational Ability	Running the model	Visual

### **3.3.4 Using historical models as a source of innovation for teaching**

In Gilbert’s model categories described historical models mean older and superseded consensus models. The origin of these models is depicted to be in a specific historical context. Also Nersessian refers to models and modelling in science history in this way paralleling the processes of learning and doing science. According to her, modelling was

often a starting point in historical cases constructing new representations in science, and so this kind of researcher's mental modelling played a central role in the historical processes (Nersessian 1999, 14; Nersessian 2002b, 137; Nersessian 1995).

Science education has been criticised for concentrating on teaching too much the products of long concept formation processes (like formulas), and forgetting the procedural nature of science (Justi 2000, 209; Kurki-Suonios 1994, Kurki-Suonio 1998) One main point of using the history and philosophy of science (HPS) in science is the belief that science education should emphasise more the processes through which the scientific knowledge is produced. Galili and Hazan (2000, S5) have put it more directly: "Although limited in extent the recapitulation of science history in the growth of individual knowledge indicates similarities between the conceptual difficulties overcome by scientists in the past and by the learner of today".

The following are examples of studies, which are searching for ways the new ideas of history and philosophy of science can be applied in science education. Some of the studies are also examples of teaching experiments, in which HPS has been used as a part of the learning process:

1) Spiliotopoulou-Papantoniou (2007) has studied models of the universe and compared children's models and historical cosmological models. The method of the research was to parallel 6-16 year-olds drawings to the historical drawings of the topic. In his analysis similarities were used as categories of description, which helped to find out analogies between the two groups' models. The study proved certain similarities in the way human beings experience the universe. According to Spiliotopoulou-Papantoniou the information about similarities and differences between children's models and historical models is valuable in rethinking classroom epistemology and planning the school curriculum.

2) In Galili's and Hazan's study (2000) used a one-year long experimental course in geometrical optics incorporating historical models of light, vision, optical images etc. The goal of the teaching was to reveal the conceptual evolution of human thought and ideas about nature. The study was carried out in a high school with 10th graders, which formed an experimental group and a control group. Moreover, the planning of the experimental course utilised research results regarding high school students' knowledge of optical phenomena. The content knowledge of students was expressed in a facet-scheme structure, and it was compared both to the control group and to formal scientific knowledge. The main difference between the experimental course and the traditional one was the straight connection to the historical growth in the understanding of the domain and discussions concerning the nature and behaviour of the phenomenon. Thus the instruction followed the historical progress of the phenomenon. (Galili and Hazan 2000, S3-S5)

3) Dedes (2005) has studied the conceptual similarities of vision between historical models and children's representations. The historical models of vision i.e. the roles of light and the eye in the process of vision were studied by a historiographical study, whereas the children's representations were based on a bibliographical review of their representations. As a result of the study Dedes concluded that there really exists some similarities between historical models and children's representations of vision, so the

knowledge of the history of science may help science education researchers and teachers to localise the origins of children's learning problems.

4) Binnie's idea is to use the history of electricity and magnetism to increase the level of teaching. According to her the historical progression of the domain including experimental works based on the originals could be applied to modern instruction. In addition, the modelling process in the history of science would better create the picture of the progressively changing conceptions of a domain. (Binnie 2001, 379, 388)

5) The International Pendulum Project (IPP) is a wide-ranging study of pendulum motion. The aims of the project are among others scientific and educational. The purpose is to improve science education by developing pendulum-related curricular content at all levels of school. (Matthews 2006) On the background of the Pendulum Project are the historical experiments of pendulum motion, and the aim is to teach students among others key features of scientific method and important aspects of the interplay between science and its social and cultural context (Matthews et al. 2004, 274).

Teaching using historical models is not so simple. According to Justi (2000), Justi and Gilbert (2000) there is a danger in science teaching to simplify too much the historical processes of knowledge by compositing several historical models to form so-called hybrid models. This kind of mixing of models does not give the right picture of different ways of thinking about a phenomenon, and the validity of a given model cannot be assessed. Neither does the progression between distinct models in history appear. According to Justi, the hybrid models can evoke problems in students' modelling processes, because they cannot know the origin of a model. Historical models are very context dependent, thus context should be explicitly explained, as well as the definition of criteria for the characterisation of each model should be made clear. (Justi 2000, 222-225; Justi and Gilbert 2000, 993, 1006).

According to Izquierdo-Aymerich and Adúriz-Bravo (2003), who represent the so-called new history and philosophy of science (NHPS), another risk in applying too close parallelisms between learning and doing science is regarding the pupil as a scientist. Instead, they have proposed that teaching and learning science should be regarded as another autonomous aspect of developing and understanding scientific knowledge. According to them models generalised in science should be adjusted to the pupils' worlds. (Izquierdo-Aymerich and Adúriz-Bravo 2003, 27, 32, 40)

In this study the historical models of DC-circuit phenomena have two roles. Firstly, from a purely scientific viewpoint, it is interesting to parallel and compare the found historical models and pupils' external representations. It is possible to compare the language used in the context of historical models and external representations to get information about forming models. Secondly, the aim is not to teach with historical models, but to utilise the concept formation processes at the background of historical models into designing the teaching experiment (phases 2 and 3). For example, the original experimentality of DC-circuit phenomena is thought to act as inspiration for planning lessons for the teaching experiment.

### **3.4 Experimental-centred representation – the approach of learning adopted in this study**

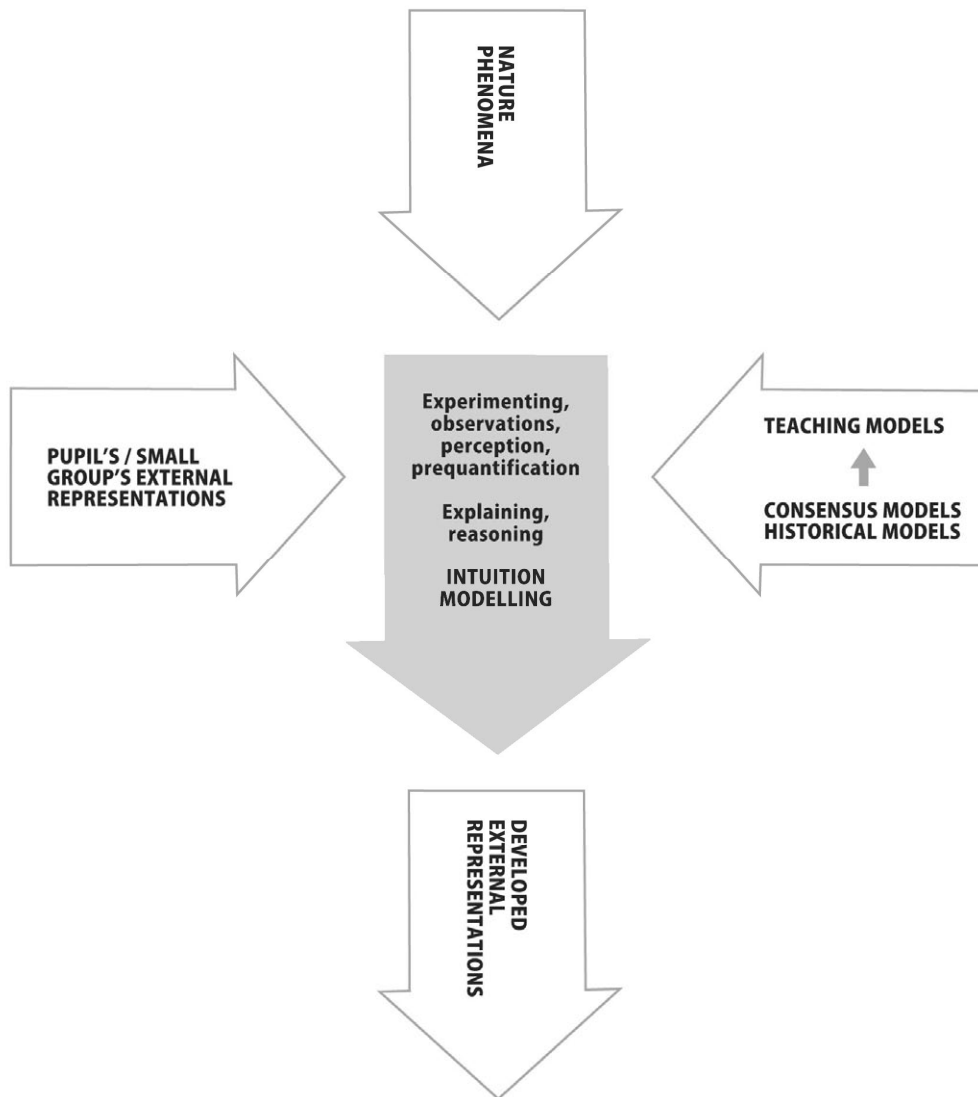
In this study two different aspects of learning and teaching physics are united, these are the perceptual approach and the model-based reasoning –approach, which were introduced in sections 3.2 and 3.3. The perceptual approach, which has been developed to promote physics learning and teaching (Kurki-Suonio and Kurki-Suonio 1994), is more empirically oriented than the model-based reasoning –approach, which originates from cognitive sciences (Nersessian 2008); while the perceptual approach gives priority to empiricism and empirical observations on the basis of forming concepts, the model-based reasoning starts from generally accepted consensus models, and forms teaching models from them. The pupil's earlier external representations are also taken into consideration.

The purpose of mixing the two approaches is to achieve an approach, which is more comprehensive than either of the two approaches alone. While the perceptual approach emphasises the role of empirical observations and perception based on them, it however does not stress so much pupil's earlier conceptions. By adding the aspect of pupil's earlier conceptions to the new approach, the learning process widens starting immediately from the pupil's previous knowledge and conceptions of the subject matter. Furthermore, the role of the teaching model is also taken into consideration, as well as the models behind it. As mentioned earlier, model-based reasoning lacks the strongest part in the perceptual approach, namely the stress on empirical concept formation. While searching for different ways of modelling subject matter by visual, analogical, simulative, or linguistic forms, it ignores the meaning of well-organised experiments and pupil's active perception based on them. Furthermore, the perceptual approach also offers more exact terms for describing the different phases of concept formation. In this study these terms are used to give names for the unspecified and disintegrated units of external representations. In the following chapter these terms are used in forming the framework of model applied in this study.

The purpose of forming the new approach is to get a concrete and comprehensive tool for analysing 1) the development of historical models of DC-circuit phenomena and 2) the development of a small group's external representations of DC-circuit phenomena during the teaching experiment. The approach will also be utilised in planning the teaching experiment in the second phase of the study.

This study focuses on learning. Learning takes place in a social context, in a small group, by talking and discussing under the guidance of the teacher. The learning process of the small group will be analysed from both aspects of learning – empirical concept formation and models – meaning that the starting point and the direction of the process can be spliced. In Figure 7 below, the process of learning is depicted starting from a small group's external representations, nature phenomena and teaching models.





**Figure 7** *Uniting the ideas of perceptual approach and model-based reasoning: Experimental-centred representation. The aim of learning (the big arrow in the middle) is to develop the original external representations towards a more developed direction.*

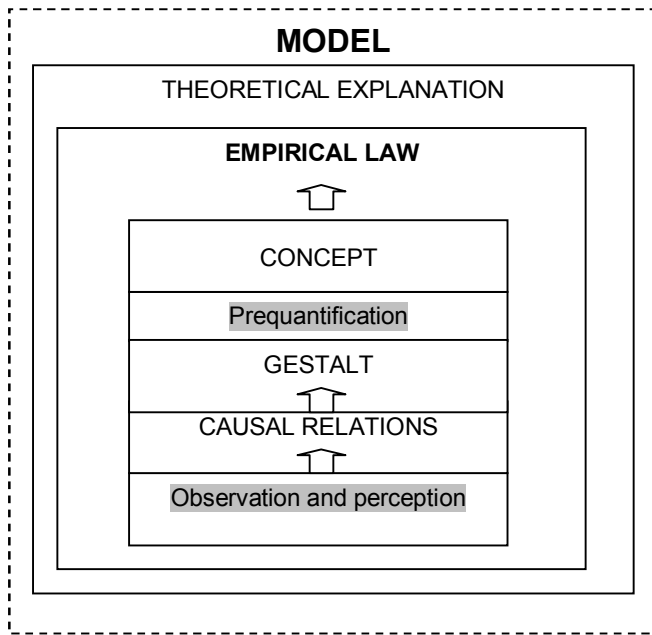
On the grounds of the approach adopted (see Figure 7 above) the learning process has three affecting factors: firstly the small group's own external representations, secondly the teacher's teaching model of the subject matter, and thirdly the nature phenomena. The teaching model is based on the generally accepted consensus models, and also historical models can be used as a view for planning the teaching model. The teacher's role is to plan the teaching model, and choose suitable nature phenomena to be observed on the grounds of the teaching model and pupils' external representations. Thus, from the pupil's point of view, learning physics starts from his/her earlier representations. These external representations are developed by way of the teaching model, and with studying the empirical phenomena chosen by the teacher.

The learning situation in the classroom is a mixture of empirical operations like experimenting, observations, perception, and prequantification of nature phenomena, and modelling operations like explaining and reasoning. These operations are understood to take place in small group discussions and argumentations as a part of higher-order thinking (see section 2.2.2). A special feature in a part of experiments is the use of the connection cards (see section 6.6.1), in which case the use of cards simulate real DC-circuit phenomena. Furthermore, the intuition of human mind also has an essential role in modelling. The process of learning is cyclic meaning that pupil can use his/her higher-level developed representations again in reasoning and explaining operations of the same kind of phenomena. The role of the teacher is also active in this phase. The teacher guides and helps the pupil's modelling process towards higher levels by using teaching models as a tool for guidance.

On the basis of aspects described in this chapter the new approach is named *an Experimental-centred representation*. The name highlights on one hand the meaning of experiments and perception in small group's learning process, on the other hand the final part of the name, representation, centres around representing as a comprehensive process of learning. Thus, in this study the external representation is the main concept describing the small group's learning towards higher levels.

### **3.5 The frame of historical models and external representations applied in this study**

In practice uniting the two approaches means forming a tool of analysis for the content analyses of the study. As described in section 3.2, the concept formation processes in physics can be portrayed by hierarchical levels of developing knowledge. In this study the subject matter, the analysed DC-circuit phenomena belong to the qualitative level of knowledge, and thus the conceptualisation mainly follows the perception phase of conceptualisation (see section 3.2.1). Thus, to the frame of model are included fragments typical of this phase: *observation and perception, understanding causal relations, forming of gestalts, doing prequantitative experiments, and finding concepts and empirical laws between them*. This modelling can also include the first theoretical explanations of DC-circuit phenomena. Figure 8 below, displays the framework of a model designed for this study. So, the historical models and small group's external representations are supposed to be composed of fragments of this kind. These fragments are supposed to appear in a form of external representation, which means small group's explanatory and reasoning talk, or researcher's written texts. Including all phases of empirical conceptualisation to the frame of historical models and small group's external representations enlarges and specifies the field of models, so the learning process is able to be followed more accurately than earlier.

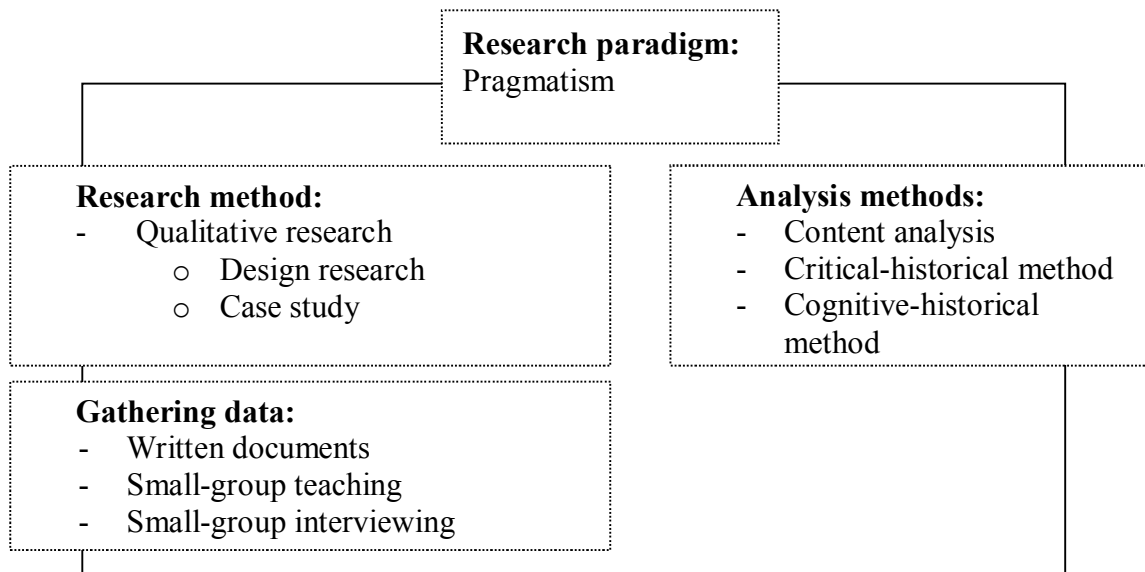


**Figure 8** *Framework of a model applied in this study. The model describes the fragments belonging to a model at the qualitative level of knowledge.*

In this study, the framework of a model (Figure 8) is applied as a tool both in analysing the historical concept formation processes and pupil’s learning process of DC-circuit phenomena in a small group. For example, in a situation where a pupil understands that unfastening a conducting wire from a battery fuses the bulb, his or her external representation of the electric circuit might have the following kinds of fragments: 1) The bulb fuses (observation). 2) The wire is needed to close the circuit (perception, gestalt). 3) The bulb fuses, because electricity does not reach the bulb (theoretical explanation, causal relations, partially incorrect). Figure 35 illustrates a small group’s fragment map of the external representation of the electric circuit, which has been produced on the basis of the framework of a model. In the case of the electric circuit there are not the phases of prequantification and an empirical law, because the developing concept is not a quantity (like the electric current and the source voltage). In chapter 5 we present historical models of DC-circuit phenomena. For instance, Figure 23 portrays the historical model of a closed circuit including the fragments belonging to it in the age of Volta. Because of different kinds of data used in analysing historical concept formation and small groups learning, the figures describing the models differ from each other. On the grounds of historical data, it is not as easy to follow all the thinking paths as in the case of small groups learning. In Volta’s articles the whole process of thinking are more “ready” or processed than in the small group’s negotiations, which can be traced thought by thought.

## 4 Research paradigm and methods

The research paradigm and methods applied in a study are based on the researchers' understanding of reality and their possibilities to get knowledge about it. This chapter contains a description of the research paradigm and the methods used in this study. Firstly, the research paradigm, philosophical assumptions and stances – like ontological and epistemological beliefs, which have guided the planning of the research, will be described. Secondly, the concrete research-, data gathering-, and analysing methods based on the paradigm, will be depicted. Figure 9 summarises the research paradigm and methods used.



**Figure 9** *Research paradigm and methods followed in the research.*

### 4.1 Pragmatism

The traditional paradigms at the background of educational research are positivism and constructivism, these are usually seen as contradictory philosophies. Between the two main philosophies there have been positioned paradigms of postpositivism and critical theory (Guba and Lincoln 1994). Moreover in recent years, a participatory paradigm that is positioned next to constructivism, has been proposed (Lincoln and Guba 2000, 170). In another classifications, the paradigms between the extremities are postpositivism and pragmatism (Tashakkori and Teddlie 1998, 23) or pragmatism and dialectical positions (Rocco et al. 2003, 21).

According to the positivistic view, the research observer is separate from the entities, which are under observation. Thus the knowledge gained is objective in nature. Moreover, according to positivists, research can be done without biases or emotional feelings. The constructivists view of knowledge is the opposite: they believe that knower and known cannot be separated, because knower is subjective and the only source of reality, which

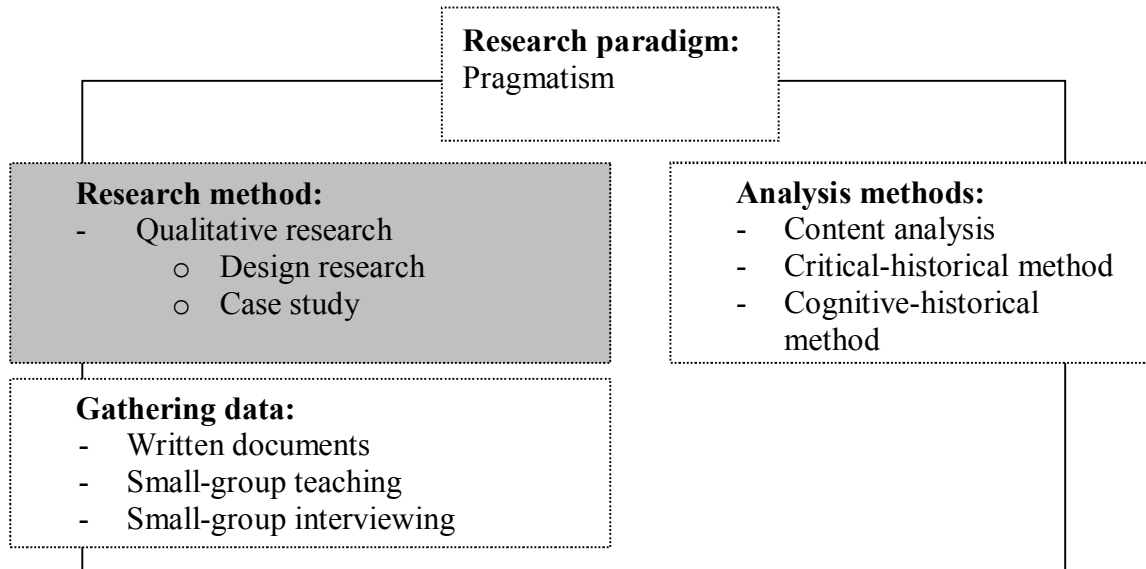
also makes the knowledge subjective. Furthermore, for constructivists there are many possible constructions of reality, whereas according to positivistic ontology there is only one reality. They also see research as value-bound. From the point of methods used positivistic orientated research uses quantitative and constructivism applies qualitative methods. In addition the aim of inquiry in positivistic oriented research is to explain, predict and control, whereas in constructivistic research the aim is to understand and reconstruct. (Johnson and Onwuegbuzie 2004, 14; Lincoln and Guba 2000, 166, 168; Guba and Lincoln 1994; Tashakkori and Teddlie 1998, 23)

In recent years pragmatism has been proposed as an alternative philosophical grounding for educational research. The philosophy originates from the work of Dewey, James, and Pierce, whose original aim was to provide an answer to the mind-body problem that is to say in acquiring knowledge of a material world by an immaterial body. Philosophically pragmatism is placed between positivism and constructivism stating that knowledge is on one hand subjectively constructed, but on the other hand it is based on the reality of the world we experience and live in. In pragmatism the epistemic distinction between subject and external object is replaced by a naturalistic and process-oriented organism-environment interaction making the different roles of researcher and object possible. (Johnson and Onwuegbuzie 2004, 16, 18; Juuti and Lavonen 2006, 57)

The reason for highlighting pragmatism in educational research is its nature of linking theory and praxis, thus the results of the research are possible to be applied for teaching (Greenwood and Levin 2005, 53). The main idea of pragmatism is to start from the research questions and think what philosophical or methodological approaches work for the problems (Rocco et al. 2003, 21; Johnson and Onwuegbuzie 2004, 18). In this study the need for a pragmatic approach appears especially in the teaching experiment (phase 3), where questions on the focus, pupils' external representations, are reached by different ways of activating their talk.

## **4.2 Research method: qualitatively orientated research**

The philosophical frameworks described above have their corresponding research methods, which apply the philosophical groundings. Generally speaking, quantitative research is based on positivistic philosophical views, qualitative research in relation to constructivism. Between the two main method branches there exists so-called mixed research, which leans on pragmatism.



**Figure 10** *Research methods applied in this study.*

Table 4 depicts the differences between qualitative and quantitative research methods, and describes the components of mixed research. The emphases highlighted in this study are printed in bold text.

**Table 4** Comparing the different emphases of quantitative, qualitative and mixed research methods (Johnson and Christensen 2004, lecture 2). The foci of the research in this study have been printed in bold text.

	<b>Quantitative Research</b>	<b>Mixed Research</b>	<b>Qualitative Research</b>
<i>Science method</i>	Deductive or “top-down” The researcher tests hypotheses and theory with data	<b>Deductive and inductive</b>	Inductive or “bottom-up” The researcher generates new hypotheses and grounded theory from data collected during fieldwork
<i>View of human behaviour</i>	Behaviour is regular and predictable	<b>Behaviour is somewhat predictable</b>	<b>Behaviour is fluid, dynamic, situational, social, contextual, and personal</b>
<i>Most common research objectives</i>	Description, explanation, and prediction	Multiple objectives	<b>Description, exploration, and discovery</b>
<i>Focus</i>	Narrow-angle lens, testing specific hypotheses	<b>Multiple focus</b>	Wide-angle and “deep-angle” lens, examining the breadth and depth of phenomena to learn more about them
<i>Nature of observation</i>	<b>Attempt to study behaviour under controlled conditions</b>	Study behaviour in more than one context or condition	<b>Study behaviour in natural environments</b> <b>Study the context in which behaviour occurs</b>
<i>Nature of reality</i>	Objective (different observers agree what is observed)	<b>Commonsense realism and pragmatic view of world (i.e. what works is what is “real” or true)</b>	Subjective, personal, and socially constructed
<i>Form of data collected</i>	Collect quantitative data based on precise measurement using structured and validated data collection instruments (e.g., close-ended items, rating scales, behavioural responses)	Multiple forms	<b>Collect qualitative data (e.g., in depth interviews, participant observation, field notes, and open-ended questions)</b> <b>The researcher is the primary data collection instrument</b>
<i>Nature of data</i>	Variables	Mixture of variables, words, and images	<b>Words, images, categories</b>
<i>Data analysis</i>	Identify statistical relationships	Quantitative and qualitative	<b>Search for patterns, themes, and holistic features</b>
<i>Results</i>	Generalizable findings	<b>Corroborated findings may generalize</b>	<b>Particularistic findings</b> <b>Representation of insider (i.e., “emic”) viewpoint</b> <b>Present multiple perspectives</b>
<i>Form of final report</i>	Statistical report (e.g. with correlations, comparisons of means, and reporting of statistical significance of findings)	<b>Eclectic and pragmatic</b>	<b>Narrative report with contextual description and direct quotations from research participants</b>

As seen from the table, mainly qualitatively oriented aspects of research are applied in the study. However, from the standpoint of *science method* the study places on the field of mixed research because of the abductive (Tuomi and Sarajärvi 2002, 95-99; see more in section 4.4.1) nature of method for analysing empirical data, which is a mixture of deductive and inductive method. Also in the case of the *view of human behaviour*, the emphasis is somewhat mixed. This means that apart from human behaviour being supposed to be fluid, dynamic, situational, social, contextual, and personal, there can be also predictable aspects like universal misconceptions, which lead pupils' behaviour in a learning situation. *Most common research objectives* are qualitative as they focus on description, exploration, and discovery. The *focus* in this study is somewhat multiple, because the aim is both to use a narrow-angle lens like in quantitative research to study specific modelling processes, and to undertake an in depth according to the qualitative research-style. The *observation* of the teaching experiment is not done in a natural class situation, but the behaviour of a chosen small group is studied separately. However, the learning situation is very similar to a typical small group working in a classroom. Furthermore, the study uses *commonsense realism* when emphasising objectivity or subjectivity according to the situation. An attempt is made to strive for objectivity in the analysis by describing the analysis for different researcher (see chapter 8). On the other hand, the subjective nature of the socially constructed knowledge is recognised. From the standpoints of *data collection*, *nature of data*, and *data analysis* the study follows mainly the qualitative tradition of research. However, using semi-structured interviews and instructions is typical for both the qualitative and quantitative traditions (see for instance Rocco et al. 2003, 22). Moreover, in the case of research question 2.1, while analysing the levels of pupils' talk a more quantitative approach is used by arranging the categories of talk in an ordinal scale. In contrast, in the ways of representing *results* and writing the *final report* there are also characteristics of mixed research, because the results may be generalised to some extent and more developed forms of representation like fragment maps are applied in the report (see section 7.3).

In conclusion, despite of partial characteristics of mixed research, this study can be regarded as a qualitatively orientated work. Of the two different phases of study, phase 1 of historical modelling of DC-circuit phenomena and phase 3 of teaching experiment in a small group, the former is more based on qualitative research, whereas the latter has also weak characteristics of mixed research.

#### **4.2.1 Design oriented research tradition**

Many approaches from different backgrounds can be used in the design oriented research tradition. A connective factor in this tradition is the linking of research and instructional practice (Duit 2006, 9). For example design experiments (Brown 1992), didactical engineering (Artique 1994), design research (Edelson 2002), and design-based research (Design-Based Research Collective 2003) are typical examples of this research tradition. Moreover, the model of educational reconstruction (Duit 2006) has a strong element of design in it. The approaches have different emphases in relation to design and research.

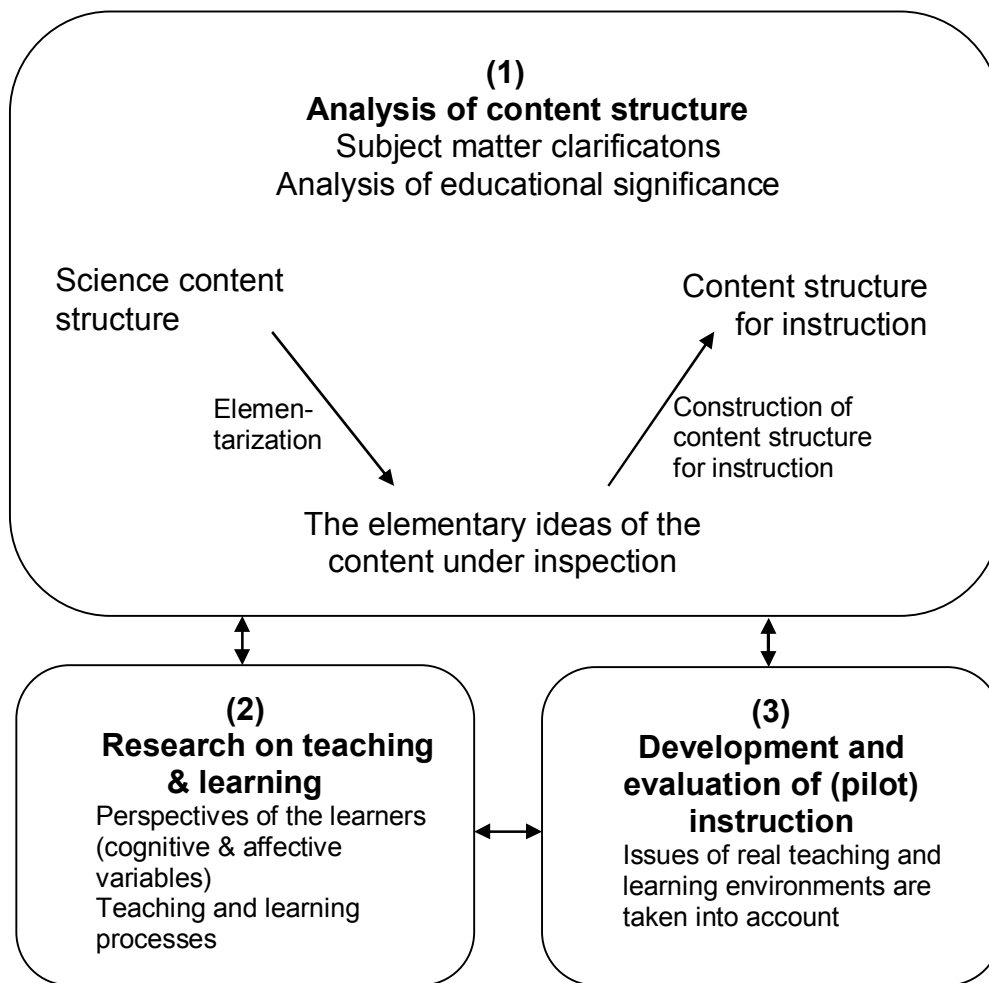


While the design-based research is “from a design to a research” –orientated approach (Juuti and Lavonen 2006, 59), the model of educational reconstruction uses research as a starting point for the designing process (Duit 2006, 5-8).

Besides the important aim of science education research –to better understand teaching and learning— the new knowledge is also essential for education. However, the general problem is that the results achieved in science education research do not generally transfer to school teaching to improve the level of teaching. The design-based research approach has been suggested as a solution for the gap between science education research and science teaching. Design-based research unites empirical educational research and the theory-driven design of learning environments. The aim of the research is to find out “how, when, and why educational innovations work in practice”, so both parties –designer (e.g. researcher) and practitioner (e.g. teacher)- have an essential role in the process. Moreover, the third party, the design artefact (e.g. web-based learning environment for science education) is developed during the co-operation. (Design-Based Research Collective 2003, 5)

According to Juuti and Lavonen (2006, 65) the aspects that constitute design-based research are the generation of an artefact that can be applied widely, the iterative nature of the process in seeking a dynamic balance, and the new educational knowledge that promotes teaching, learning, or designing educational innovations. Design-based research usually has different phases. Typical features of the research are its cyclic and iterative stages: the same stages can happen many times during the whole project. Revisions and inventions are made on the basis of feedback (Cobb et al. 2003, 10; Juuti and Lavonen 2006, 65). One proposal is the following: 1) Draft the initial goals. 2) Build an explicit model of student’s knowledge and learning in the goal domain. 3) Create an initial design for software and activities. 4) Investigate the components. 5) Assess prototypes and curriculum. 6) Conduct pilot tests in a classroom. 7) Conduct field tests in multiple classrooms. 8) Recurse. 9) Publish. (Clements and Battista 2000, 763-774) The procedure of design-based research is not fixed, but it is flexible depending on the goals and the subject matter.

Another design-oriented approach, the educational reconstruction model links research, development and instructional practice a very similar way as in design research (Duit 2006, 8-9). The model consists of three successive or parallel processes, which form a cyclic structure. According to Duit the first phase of educational reconstruction is the analysis of content structure, in which the subject matter is clarified for the topic under inspection. To this analysis belong science concepts and principles, science processes, views of the nature of science etc. For example textbooks, the historical development of the topic, and students’ pre-instructional conceptions can be taken into account. The second phase includes research on teaching and learning. In this phase are examined students’ pre-instructional conceptions and affective variables. The third phase, development and evaluation of (pilot) instruction concerns the designing process of the learning-supporting environment. The design is based on earlier phases. The materials and activities designed are also evaluated in this phase. (Duit 2006, 7-8)



**Figure 11** *Duit's model of educational reconstruction. (Duit 2006, 5)*

One example of recent design-based research is the ASTeL-project in which a web-based learning environment for learning and teaching physics in the lower classes at primary school was planned. The research procedure consisted of 1) needs assessment; 2) definition of the objectives for a design solution; 3) design and production of the material; and 4) evaluation of the material. In this research the different phases were reported in series: needs assessment (Juuti, Lavonen, Kallunki and Meisalo 2004), limited test of prototype (Juuti, Lavonen, Kallunki and Meisalo 2002), and pilot test (Juuti, Lavonen, Kallunki and Meisalo 2003). In Aksela's study the design research approach (Aksela 2005, 12-13) was used. Her study developed a computer assisted learning environment to support meaningful chemistry learning and higher-order thinking. The main elements of this study were theoretical problem analysis and empirical problem analysis, which aimed to design of a rich learning environment. Nurkka's research (Nurkka 2006, 65) is an example of using the model of educational reconstruction in designing, developing, and evaluating the teaching-learning sequence on the moment of force in physiotherapy training. The main phases of the research were the analysis of content, the empirical research, and the design of the instruction.

According to Juuti and Lavonen (2006) design-based research can be considered as pragmatism based method. They explain the connection by the very pragmatic nature of design-based research. In design-based research reflection between teaching, knowledge about science teaching and learning is continuous, so the connection to classroom is straight. As mentioned in section 4.2, pragmatism's new conception in subject-object controversy has formed the role of knowledge as an organism-environment interaction. In the case of design-based research the place of knowledge is in the interaction of teacher – the learning environment. The interaction is seen as an active, adaptive, and adjustive process, in which every party can propose changes to the learning environment. (Juuti and Lavonen 2006, 57-58)

#### **4.2.2 Design research in this study**

This study will be realised as a design research, which has been influenced by the design-based research approach and the educational reconstruction model. The study will be realised in one cycle, which begins by research, continues by design and ends in the research phase. The first phase of the study analysis of content structure is research-orientated, the second phase designing the learning content emphasises the designing work, and the last phase instruction and evaluation realises the design solution and investigates learning. The whole cycle with its sub-phases is described in Figure 1.

In the first phase of the study, the history of DC-circuit phenomena is analysed by content analysis. This means carrying out research into the experimentality of the DC-circuit phenomena and the historical models. This analysis is done in the spirit of the critical-historical and cognitive-historical methods (sections 4.4.4 and 4.4.5) to find out the main features of the historical models. The found historical models are then compared with pupils' common external representations reported in previous science education research (see section 6.2) of the subject matter. Furthermore, in the background of the analysis are the scientific models of DC-circuit phenomena. The first phase of the study investigates the first research question 1: *How did the historical models of DC-circuit phenomena develop in Volta's time?* See the results in 1 in chapter 5.

The second phase in the design research includes the concrete designing work and the charting of needs assessment (6.1). In this phase the teaching models for instruction are designed (see results 2 in chapter 6). In addition, the prototype of instruction is tested (see section 4.2.3).

The third phase of the study consists of the realisation of the actual teaching experiment (see section 6.7 and the evaluation section. The empirical data is analysed by content analysis (see section 4.4.1) and as the results we obtained answers to research question 2: *How will the small group's external representations of DC-circuit phenomena develop during the teaching experiment?* The results are depicted in chapter 7.

### 4.2.3 Design procedure

This chapter describes the design research process, and the members of design in different phases of the project. The chapter also includes a description of timing the process. See Table 5, Design research timetable.

The project started in 2000 with research into the historical models of electric current (phase 1). In this phase I was the only participant at the time. During autumn 2001 a needs assessment for the teaching experiment was done as part of another design project (Juuti, Lavonen, Kallunki and Meisalo 2004; see the details in section 6.1). After completing the phase of the historical models the project was continued with undergraduate student, Laura Karhunen. In this phase (continuing phase 1) the task was to compare the historical models found in the science education literature with reported pupil's external representations of DC-circuit phenomena. The results of this phase were reported in ESERA 2003. The co-operation with Laura also included doing initial plans to analyse her data of learning DC-circuit phenomena at high school level (Karhunen, Koponen and Kallunki 2003). The aim of the co-operation from my side was to set up the last phase (3), the realisation of the teaching experiment. The design work (phase 2) for the teaching experiment was done in autumn 2003 with undergraduate student, Saija Lehtonen. The planning included meetings with my supervisors, and class teachers.

Testing the prototype of the teaching experiment (continuing phase 2) was done at Vallila Comprehensive School (Lower stage), on the 2<sup>nd</sup> of February 2004. During the test a pilot of a preliminary interview for a chosen group of four pupils was done. Also the first two lessons of the teaching experiment were tested on the whole class of 26 pupils of 5<sup>th</sup> graders. The aim of the piloting was to test technical details and subject matter, and on the basis of it, the main change to the lessons was to choose only one small group for the final teaching experiment. This modification was done for technical and subject matter reasons: it was difficult to videotape in the classroom because of the background noise, and it seemed plausible that the chosen small group would concentrate better on the content in a more peaceful place. Because the purpose of the research was to focus on small group learning, not to the whole class, it was decided to go ahead with this change. Thus this change meant the study was done in unnatural experimental situations. The studies of De Vries et al. (2002) and Sherman and Klein (1995) were also done by making the same kinds of compromises to increase the researcher's control over interfering variables. In these studies separate pairs of students worked in a special laboratory outside the classroom (Bennett et al. 2004, 56).

The final teaching experiment week (phase 3) took place at the end of February 2004 at Helsinki Second Teacher Training School in Viikki (Lower stage). The teaching experiment consisted of three interviews (preliminary interview, intermediate interview and final interview) and five small group lessons. The same experiment was realised for a small group of third-graders and fifth-graders. See section 6.7 for more detailed information. See also Table 5 and Table 6 below for the timetables of the whole design research and the teaching experiment.

**Table 5** *Design research timetable.*

<b>Phase of the research</b>	<b>Date</b>	<b>Participants of the research</b>
Phase 1, examining historical models of DC-circuit phenomena (Kallunki 2001a), paralleling constructing concepts of DC-circuit phenomena in learning and doing science (Kallunki 2001b)	2000 – 2001	Veera Kallunki
Phase 2, Needs assessment for the teaching experiment (Juuti, Lavonen, Kallunki and Meisalo 2004)	Autumn 2001	Kalle Juuti, Jari Lavonen, Veera Kallunki and Veijo Meisalo
Continuing phase 1, comparing historical models and pupil's external representations, tentative results (Kallunki and Karhunen 2003)	Spring 2003	Veera Kallunki and Laura Karhunen *
Phase 2, planning the teaching experiment	Autumn 2003	Veera Kallunki and Saija Lehtonen
Continuing phase 2, testing the prototype of teaching experiment	February 2004	
Phase 3, realisation of teaching experiment	February 2004	
Phase 3, tentative results of teaching experiment (Kallunki 2004)	December 2004	Veera Kallunki

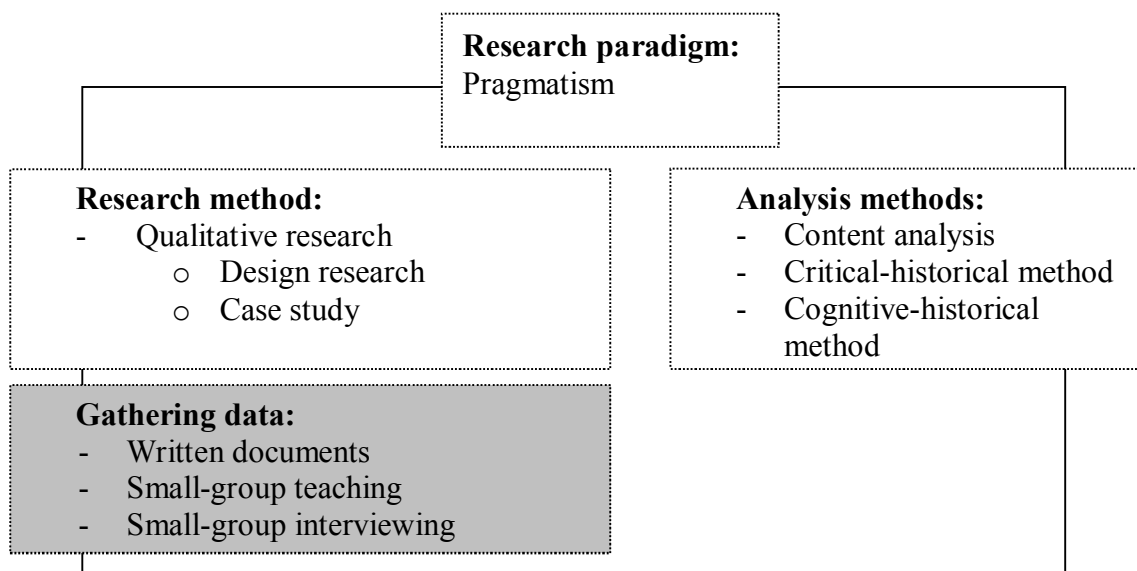
\* as a part of two partially overlapping research projects carried out by myself and Laura.

**Table 6** *Timetable of the teaching experiment. The topics of the teaching experiment are described in section 6.7 in Figure 32.*

<b>Date</b>	Mon 23 <sup>rd</sup> of February	Tue 24 <sup>th</sup> of February	Wed 25 <sup>th</sup> of February	Thu 26 <sup>th</sup> of February	Fri 27 <sup>th</sup> of February
<b>Phase of the teaching experiment</b>	9.40-10.30 Preliminary Interview 11.00-11.45 1 <sup>st</sup> Lesson	12.00-12.45 2 <sup>nd</sup> Lesson	8.45-9.30 3 <sup>rd</sup> Lesson 9.40-10.30 Intermediate Interview	8.45-9.30 4 <sup>th</sup> Lesson 13.00-13.45 5 <sup>th</sup> Lesson	10.45-11.30 Final Interview

### 4.3 Data gathering methods

In this study data was gathered in two phases. In phase 1 the historical data was gathered, and in phase 3 the empirical data was gathered. Figure 12 below sums up the sources of information.



**Figure 12** *Data is gathered from written historical documents and videotaped small-group sessions.*

#### 4.3.1 Historical data

According to Johnson and Christensen (2004) gathering historical data requires identifying, locating, and collecting information pertaining to the research topic. In historical research various sources can be used such different documents like diaries, records or newspaper articles. Also, oral histories, i.e., interviews with individuals who have knowledge of the research topic, can be used. Information sources can be either primary sources or secondary sources. The sources used must also be evaluated for their authenticity and accuracy.

In this study the historical data used includes mainly Volta’s original articles and letters (Volta 1800; VO). The data also includes some secondary sources like Pera’s research of Galvani and Volta (Pera 1992). The data has been chosen on the grounds of its content pertaining to Volta’s and Galvani’s original experiments and interpretations of DC-circuit phenomena.

### 4.3.2 Teaching in a small group

Small group learning involves studying in groups of two to six pupils. Learning strategies vary from traditional group work to collaborative learning, co-operative learning, and small group discussions. (Bennett et al. 2004, 7) In small group learning it is important that a pupil has a positive interdependence of the group members. He understands that his own working helps other group members, and respectively he benefits from other's work. Face-to-face supportive interactions results in the pupils receiving mutual positive support, this also is an essential element of group work. In addition, it is important that everyone is responsible of their own work when a group's work is divided into personal tasks. The social skills of the group members and the inner-group processing of the task are essential. (Johnson and Johnson 2002, 103, 109) The teacher's role in small-group learning is discussed in section 4.3.2.1.

So-called active learners have been characterised by the following features: 1) Initiate their own activities and take responsibility for their own learning. 2) Make decisions and solve problems. 3) Transfer skills and learning from one context to other different contexts. 4) Organise themselves and organise others. 5) Display their understanding and competence in a number of different ways. 6) Engage in self- and peer-evaluation. 7) Feel good about themselves as learners (Watts et al. 1995a, 14-15) Small-group learning has been advocated as one of a range of active learning strategies (Bennet et al. 2004, 10). This also becomes evident when compared to the essential elements of small-group work (Johnson and Johnson 2002) as listed above. Responsibility and a positive attitude to one's own learning and other's progress is emphasised.

Learning in a small group is one possibility to increase pupils' talk. Among the useful features of talking during a lesson has been the fact that discussion positively affects pupils' abilities to organise their thoughts and make decisions. Small group work also activates pupils to interpret observations through natural discussion. These kinds of pupils' activities take the focus away from the teacher and positively increase youngsters' responsibility for their learning (Bentley and Watts 1989; Lavonen 2002, 224). According to Lavonen (2002, 225) discussing is especially important in familiarising pupils with a new domain, when its role is to recognise phenomena and their properties. One other important stage in discussing is in making interpretations and conclusions on the basis of experiments. The point of discussing is particularly to guide pupils to conceptualise observations.

As discussed in section 2.2, language and talking play significant roles in learning. According to Mortimer and Scott (2003, 3) pupil's talk is a central part of the meaning making process, which takes places in a dialogic process, bringing different ideas together and discussing. From this point of view pupils need more opportunities to talk about what they are doing. This enables them to become aware of their own ideas and those of others. Also, Arons (1997, 199) emphasises pupil's opportunity to talk, argue and explain to promote learning. From the standpoint of conceptual learning, active small group discussion enables pupils to form their own meanings to observations and re-sort new information in old and new contexts (Watts et al. 1995b, 51, 74, 79; Heaney et al. 1995, 33; Rasku-Puttonen et al. 2003, 44; Enghag et al. 2007). According to Watts and Bentley

(1995, 195) the stress should be on approaches, which highlight pupils' personal experiences and prior understanding. In talking together in a small group it is possible to modify one's own ideas (i.e. mental models/pupil's internal representations) (Bennet et al. 2004, 9; Watts et al. 1995a, 12).

Bennet et al.'s (2004) systematic review of the use of small-group discussions in science teaching (Bennet et al. 2004) is the first attempt to analyse wider the general effects of small group learning. The review concludes that in spite of a wide range of studies of science lessons, small group learning itself is rarely the focus of investigation (Bennet et al. 2004, 2), thus the review proposes that particularly the nature of stimulus provided for the group and its effect on the development of understanding should be researched. (Bennet et al. 2004, 2, 6) One important finding of Bennet et al.'s review (2004, 60) was that using internal conflicts (where a diversity of views are represented within a group) or external conflicts (where an external stimulus presents a group with conflicting views) in small group discussions, resulted in a significant improvement of students' understanding of evidence. Thus, it seems to be important to produce situations, where the members of the small group really express their own conceptions of the subject matter. According to Bennet et al. (2004, 4), particularly the dissimilarity of the small group members in terms of their domain-specific understandings improves pupils' understanding. This is surely one good starting point for fruitful discussions. Emphasising pupils' abilities to get along with each other and also their general keenness to learn science is another approach in selecting the members of the small group (see section 4.3.3).

Bennet et al. (2004, 4) also conclude that supporting small group learning with instruction on arguing or discussing has a positive effect on learning. In this study, discussion and argumentation of the small group will be supported by the use of special connection cards (section 6.6.1), which make the situation democratic for all group members when they argue. Furthermore, the teacher or interviewing researcher can also support argumentation by asking pupils to use their own words in explaining their different opinions.

In this study small group learning will be used particularly to offer a learning-activating environment, in which pupils talk, argue and negotiate about their external representations of the topic. The aim is to encourage everyone to speak in order to get information about the different external representations pupils. Moreover, the goal of using a small group as "a learning centre", is to analyse the small group's (see research question 2) modelling processes during the teaching experiment.

#### *4.3.2.1 The teacher's role in small-group learning*

Despite the emphasis on the pupil's active and constructive role in small-group learning the teacher's role cannot be forgotten. In any case the pupils are novice learners, whereas teacher is an expert. The novice-expert –distinction originates from Vygotsky's conception, the zone of proximal development ZPD (see section 2.2.2), which determines



teacher's role as a supporter of learning. The teacher is the expert who guides the novice (pupil) towards better learning achievements than he/she could achieve alone.

The teacher's guiding and expert role becomes evident from Mortimer and Scott's (2003, 17-21) list of the three fundamental tasks of a science teacher: Firstly, the teacher introduces and develops the scientific story. This means familiarising pupils to the phenomenon to be learned. The second task is to support pupil's internalisation process i.e. gradual developing of the meanings for the new concepts. This stage especially needs the role of expert described by Vygotsky. The final part of the teaching involves providing the pupils opportunities for practicing and making those ideas their own. This means handing over responsibility to the pupil.

Johnson and Johnson (2002, 103-105) have also determined a different grade of roles for teaching a small group. If the pupils are learning in a formal small group the role of the teacher is strongest. In this case teacher formulates specific educational aims for every lesson, decides beforehand the grouping and roles of pupils, clearly determines the tasks and co-operation in a group, and guides and evaluates group working. In informal groups the teacher's role is clearly weaker. Their main tasks here are to guide introductory, intermediate, and final discussions. In the case of base groups learning is nearly independent of the teacher's guide.

According to Huber (2003, 267) pupils can be classified into the groups of uncertainty-oriented and certainty-oriented on the grounds of their ability to act in a small group situation. For uncertainty-oriented pupils the openness of learning tasks is an activating factor, where as certainty-oriented pupils prefer more the structuredness and guidance of the tasks. In the latter situation the role of teacher in applying small group learning is emphasized.

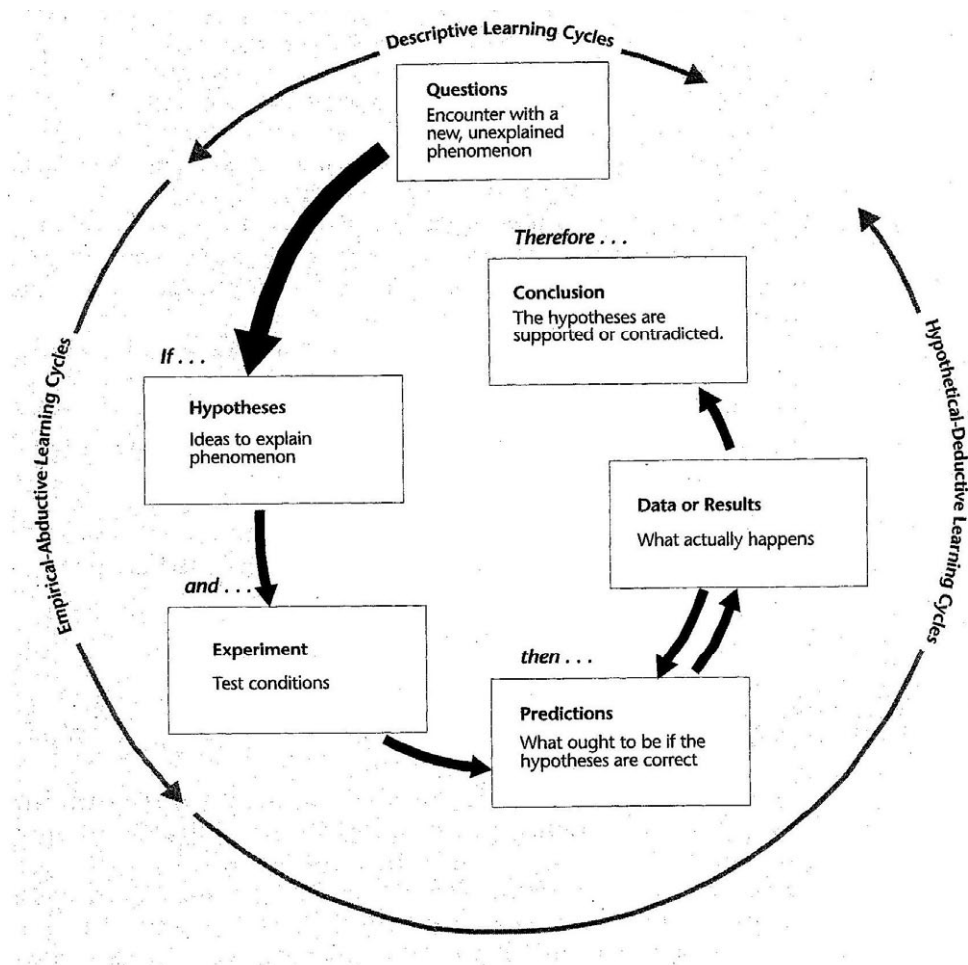
Kirschner et al. (2006, 80, 83) have criticised using too open learning strategies. According to them, especially for novices or intermediate learners direct instructional guidance is better than minimal guidance teaching. A special focus of Kirschner et al.'s approach, are constructivist-based learning strategies like discovery learning, which they argue to be generally minimally guided. Shaffer states that Kirschner et al.'s opinion is too black-and-white, the traditional open-ended discovery learning and Kirschner et al.'s "the presentation and explanation of knowledge" are not the only alternatives available (Shaffer 2006).

In this study the pupils' have active and creative roles as small-group learners. However, this does not mean that teacher is in the background. In the teaching experiment (phase 3) the teacher follows the design solution, which includes plans for the subject matter; pedagogical stand points and a structural master plan for instruction (see chapter 6). This kind of particular advance planning, and the guiding role of the teacher makes the small group learning formal meaning for the role of the teacher strong. The role of the teacher during the teaching experiment of this study will be described in section 7.4.

#### *4.3.2.2 Using learning cycles in small group learning*

The aim of using learning cycles is to activate learning by means of taking pupils' earlier concepts into account, provoking argumentation, doing predictions, and constructing concepts on the basis of the process (Lawson 2002, 133). Learning cycles, which originated from the work of Piaget, have been used in teaching from the 1960s. Karplus' learning cycle has also been influenced by Piaget's work. According to Lawson (2002, 147-8) doing science – learning by example – is a continuous and cyclic process, in which can be differentiated various phases. A learning cycle refers to a flexible instructional model. For example, in Karplus' cycle there are the following phases: 1) Exploration. In this phase pupils learn with minimal guidance and are expected to raise questions they cannot answer themselves. 2) Introduction of a concept. The teacher introduces and explains a new concept. 3) Application. The concept is applied in a new situation. Learning takes place during repetition and practice. (Karplus 1977) Respectively, Lawson classifies different forms of learning cycles as follows: 1) On the lowest and the most simplest level of using the learning cycle, a descriptive learning cycle, the stress is on describing natural phenomena. 2) On the contrary, generating hypotheses and planning experiments to test hypotheses rises the phase of learning to the next level, meaning an empirical-abductive learning cycle. 3) The highest level of learning cycle – hypothetical-deductive learning – includes testing alternative hypotheses and making conclusions about them.

The different types of learning cycles demand different levels of thinking from the students: 1) Descriptive learning requires empirical-inductive patterns like seriation (putting things in order), classification, and conservation. 2) In empirical-abductive learning the student uses empirical-inductive and some higher-order patterns. 3) The highest type, hypothetical-deductive learning demands the use of higher-order patterns like controlling variables, correlational thinking and hypothetical-deductive thinking (Lawson 2002, 139). The three different types of learning cycles can be used in different situations depending on the pupils' ages, goals of learning etc.



**Figure 13** *The major differences among the three types of learning cycles (Lawson 2002, 148).*

Regardless of the cycle chosen, the learning cycle always includes the three basic phases called exploration, term introduction, and concept application (Lawson 2002, 136-137). By exploration is meant exploring new phenomena with minimal guidance to raise questions and complexities. The goal is to create situations, which lead to hypotheses and testing. The second phase, term introduction, introduces a new term that relates to earlier explorations. The phase also includes more exploration of the subject. In the last phase of the learning cycle a new concept is applied to additional examples to extend the range of applicability of the new concept.

Using learning cycles fits well to the approach of learning adopted in this study (section 3.4). Focusing on pupil's active learning and uniting the ideas of perceptual approach and model-based research makes learning happen naturally in cycles. In the third phase of this study small group's learning can be described as freely following the ideas of the hypothetical-deductive learning cycle. This means that the teaching experiment includes questioning, making hypotheses, experimenting, predicting, processing data and results, and making conclusions as natural forms of small group working.

#### ***4.3.2.3 Small-group teaching and interviewing as a tool for gathering empirical data***

In the background of gathering empirical data is the wide research of small-group learning introduced above. Data of small-group learning situation can be collected using so called group interview methods. These methods rest on Piaget's (Ginsburg and Opper 1969, 118) clinical method, which emphasises the following: 1) Concrete objects are used as part of an interview. These objects can be referred to during the interview. 2) Practical work is emphasised. The interviewee can answer by doing an experiment instead of talking. 3) Questions are adapted to the situation.

McDermott and Shaffer (1992, 995) have also proposed doing experimental laboratory work as a part of an interview. According to them this type work can be thought to act as a template for discussions. Moreover, White and Gunstone (1992) recommend a semi-structured interview, which includes simple experimental work. The interviews could consist of the following phases: making hypothesis, observing and explaining. In Myhill et al's study children were interviewed in small groups after the small group learning. According to Myhill et al. the group interview may even support learning when the children have subsequent possibilities to construct meanings (Myhill et al. 2006, 45).

Schoster and Aufschnaiter (1999, 301-303) and Aufschnaiter and Aufschnaiter (2001; 2003) have described the group interview as a tool for gathering data. In their researches pupils sit in a groups of three round a table. The working of small groups is guided by task cards, which include the information of the work to be done. If a group is not getting on, the teacher can give them a knowledge card to help them. The data is collected by videotaping.

Hestenes (1992, 33) has introduced a Socratic method in physics instruction. This method is student centred and based on reflective instruction. This kind of learning activates students' thinking processes and gives more responsibility to them. The focus in a dialogic-talk-like-Socratic method is thinking. The method promotes critical thinking and concentrates more on the process than the outcome (Myhill et al. 2006, 25).

#### **4.3.3 Gathering empirical data in this study**

In this study the empirical data was gathered from the lower stage grades (3 and 5), at Helsinki Second Teacher Training School in Viikki. As discussed above, the prototype of the teaching experiment had been earlier tested in another school (see section 4.2.3). The interviews and lessons dealt with DC-circuit phenomena (for more see section 6.7). The same experiment was realised for a small group of third-graders and fifth-graders. The pupils worked in mixed four person's small groups consisting of two boys and two girls. All the interviews and lessons were videotaped.

The nature of the teaching experiment was almost like a normal lesson. The group size was different, but the role of the teacher was active and guiding. However, the pupils were given a lot of time and powers to work as a self-ruling learning group. Both interviews and

lessons included making hypotheses, experiments, talking, negotiating, explaining, games, drawing and writing.

During the teaching experiment attempts were made to make the talk used more understandable for pupils by 1) avoiding the use of new scientific terms before pupils understood or used them themselves 2) asking pupils to explain what they were talking about in many ways like telling more, or showing the same thing with connecting cards. The new concepts were determined and named after the meaning was understood.

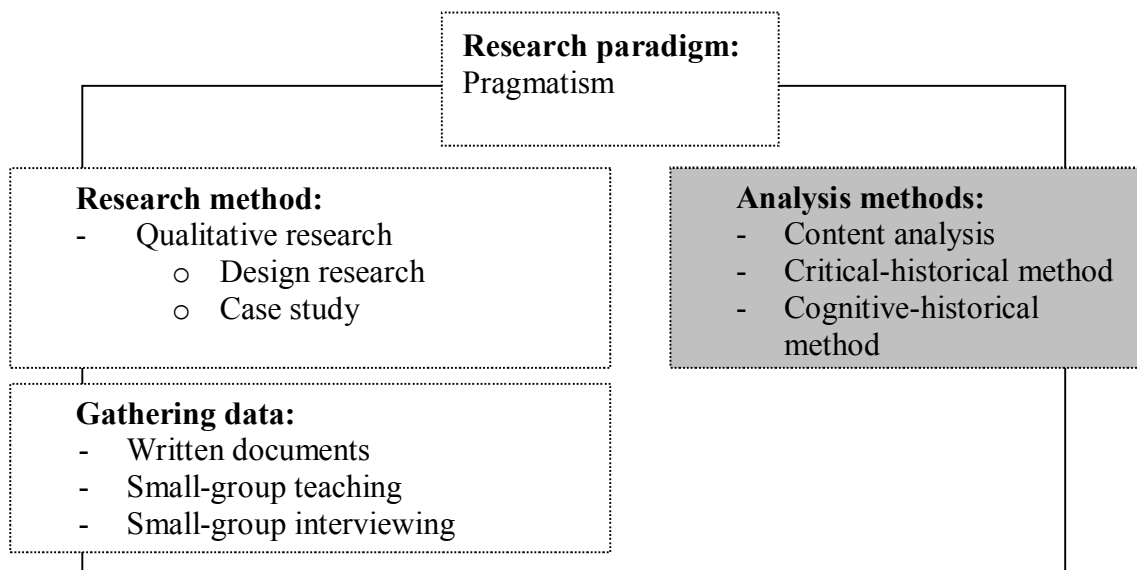
The instruction and interviews were in certain way like the Socratic method. The teacher and the interviewer used a semi-structured lesson/interviewing plan asking questions to activate pupils' thinking. The focus was on pupil's talk.

The pupils were chosen by their class teachers by the aid of given criteria (see Appendix 1: Criteria for choosing pupils for the teaching experiment). The criteria are in accordance with an elite sample, which is normally used in quantitative research, but which is suitable for qualitative research as well. The criteria selected pupils, who are supposed to be the most suitable to give information (Tuomi and Sarajärvi 2002, 88-89). Because the aim was to compose a well functioning small group, which can work together, it was important that pupils got along with each other. Moreover, the chosen pupils were generally keen, extrovert, and at the intellectually average level of the whole class. It was especially desired that pupils were used to oral expression and thinking aloud. Also in this respect the ideal group member was an average pupil, the pupil should not be too shy or dominant. Furthermore, the pupils were not to be too interested in natural sciences.

#### **4.4 Analysis methods**

In this study the analyses done in phases 1 and 3 follow the general principles of content analysis. Analysing the historical data in the first phase is done as a content analysis of texts of historical documents. As particular aspects of analysing historical data the views of two historically orientated methods are applied. The first method – the critical-historical method – highlights the history of the science dimension of the work emphasizing criticality and aspects that respect contemporary science, whereas the second method – the cognitive-historical method – points out the cognitive processes of past science and learning as connecting factors (see sections, 4.4.2 and 4.4.3).

The analysis method used in the third phase of the study is also content analysis, which uses the videos of the teaching experiment as data. The purpose of content analysis is to go into the level of language of physics and deal with pupils' external representations of DC-circuit phenomena. (See section 4.4.1)



**Figure 14** *Analysis methods in this study.*

#### **4.4.1 Content analysis for historical and empirical data**

Content analysis is widely used analysis method in qualitative research. The method is suitable for analysing written, heard or seen contents; it is typically used in qualitative research. Content analysis generally includes the following phases: 1) limitation of the data, 2) transcription of the data, 3) analysing the data by way of classifying, and 4) writing a summary (Tuomi and Sarajärvi 2002, 13, 93-95). The limitation of the data can be done for example by choosing certain parts of the data to be analysed. One example of limitation is to choose a certain amount of critical episodes or critical moments of the whole data and analyse only these. According to Nurkka and Viiri (2005, 694-695; see also Viennot et al. 2004) the critical episodes can be chosen on the basis of previous research of typical difficulties on the subject matter, and by picking the most important episodes of learning. In this study the critical episodes are chosen to describe the best learning situations. The choice was made to best answer the research questions. The chosen episodes and grounds used will be examined in section 7.1. There are also a number of different ways of transcribing data. In this study the videotaped data was transcribed with the Transana program. With the program the video and transcribed text can be synchronised to help analysis.

In content analysis, analysing phase means finding out different classes of information, and arranging data to different themes or types (Patton 2002, 463; Tuomi and Sarajärvi 2002, 95). Briefly, the purpose of content analysis is to arrange the data into a compact and clear form without losing the information included (Patton 2002, 453; Tuomi and Sarajärvi 2002, 110). In phenomenographic research, which is one class of qualitative research and which does the same kind of data arranging, the data is classified by means of categories of description (Marton 1994, 4424). Pupils' different conceptions are analysed and similarities are collected into similar categories. The data is examined many

times until different categories have stood out from the rest. Also Chi (1997) has proposed a method for coding and analysing verbal data. However, the main idea of Chi's is similar to others, the purpose of the analysis is to limit the data, segment it, code the data and look for similarities or patterns. In this study the littered data was analysed with the Weft QDA program, which is software suitable for analysing qualitative data. The program was used to help organise data into classes and to interconnect earlier classes.

In doing content analysis the researcher has to choose a logic of reasoning, this can be either inductive or deductive. In this study the logic used is inductive in the content analysis of historical data, and intermediate in doing the content analysis of empirical data. In the intermediate form of logic both inductivity and deductivity are applied, this is called the abductive approach. The rationale behind the abductive approach is to apply both the views of data grounded (inductive) and theory-driven (deductive) approaches. The abductive approach uses the earlier knowledge, but instead of purely testing the theory, the aim is to search for new thoughts. In the abductive approach the theory affects the classification of the data, because the phenomenon is already known on the grounds of theory. In this way, the theory can help the analysis. (Tuomi and Sarajärvi 2002, 95-99, 116)

The abductive approach in content analysis can be used for design research, the structure of the research used in this work. As discussed in sections 1.4 and 1.5, the structure of research in this study follows a three-phase cycle (see Figure 1 in section 1.4) and the sequential phases affect the following phases. The new phases are also based on the earlier phases. Thus, the historical models of DC-circuit phenomena found as results of content analysis in phase 1, naturally affect the teaching experiment in phase 3, and this theoretical knowledge is used as a background for content analysis.

As described in section 4.3.2 small group learning is understood to be an effective way of learning. In this study the empirical data gathered is mainly talk and discussions in a small group. Gestures are also used to check the meaning of talk in ambiguous situations (Mavrou et al. 2007, 167). Certainly, the data also includes some drawings and text, but the greater part is oral or visual data. The form of gathered data is chosen from the standpoint of the research questions set, the purpose of gathering empirical data is to get information about the development of small group's external representations of DC-circuit phenomena (see section 1.3 for research question 2).

Pupil's or small group's external representations are special conceptions of the subject matter. On the other hand, developing external representations are understood as a proof of an active learning process, which can be studied by content analysis.

Classroom discussions have recently been researched in many studies. For instance Boulter (2000), Mortimer and Scott (2003), Viiri and Saari (2006), Mortimer and Machado (2000), Nassaji and Wells (2000), Wells (1999), Scott (1998), Chan et al. (1997), and Chinn and Brewer (1998) have studied discussions from different standpoints.

#### **4.4.2 The critical-historical method**

According to the critical-historical method one aim of the history of science is to “function as an analytical instrument for the critical evaluation of methods and concepts that appear in modern science”. Thus besides the historical importance of the description of the developments of concepts, the special role of the historical course of events is also in its influence on the physics of today. (Kragh 1987, 32-33) Jammer clarifies the aim of the history of science by pointing out that the aim of it is to lead “to a profounder comprehension of the meaning of the term and to a higher level of understanding of its role and significance in physics” (Jammer 1961, VII).

The typical features of the used method are horizontality of study, anachronism vs. diachronism and criticality of study. Horizontality (Kragh 1987, 80) means that the concept formation processes are studied through time, and the topics chosen are studied during this period. The other feature of the method is the axis of anachronism vs. diachronism (Kragh 1987, 89-90). A purely anachronistic method would only study past science from the viewpoint of physics of today. In this study, however, past science also has a value of its own, so there is an aspect of diachronical history of science too. In this work diachronism can be seen in the valuation of qualitative sensory experiments and comparative experiments as an autonomic part of concept formation. The theoretical framework used is modified from the view of today’s physics, but the aim of it is not to impact on or distort the conceptual structure of the past. The anachronical view of this study appears in the clearest way in the connection of prequantitative experiments when properties are understood as forerunners of modern quantities.

#### **4.4.3 The cognitive-historical method**

Nersessian’s (2002b; 1995) cognitive-historical method is a tool to make use of past science’s practices and use it to understand learning processes for example in the case of conceptual change. The cognitive-historical method combines historical and contemporary scientific practices with cognitive science investigations of aspects of human cognition. By studying past science it is possible to get information of the practices, which scientists employ in their work. This is the “historical” dimension of the method. On the other hand, the “cognitive” dimension is used as a “lens” of the examinations of the past science. The objective of this kind of research is to “identify various cognitive practices employed in scientific cognition; to develop explanatory accounts of the generativity of the practices; and to consider, reflexively, the implications of what is learned for understanding basic cognitive processes generally”. Further, it is always possible that there might emerge some new aspects of cognition in the cognitive-historical analysis, which could even alter current cognitive science understanding.

To get information on human’s reasoning, representing and learning the cognitive-historical method makes use of all kinds of historical records of science like notebooks and publications. According to Nersessian cognitive-historical analysis can include for



example dimensions of concept formation and change, and using and developing modelling tools and instruments. (Nersessian 2002b, 135-136)

Like other historical studies in general, the nature of the first phase of this study is to find out a historical course of events, in this case the development process of the historical models of DC-circuit phenomena. The interest is thus in the historical modelling processes and also in modern conceptions of the nature of DC-circuit phenomena.

The special feature of the first phase of this work, resulting from the chosen method of research, is the interpretation, not only representation, of historical events. The interpretation is done from the point of perspective of the designed framework for the modelling process. For this purpose, schematic, graphical maps were chosen. The work has been organised so, that by using these maps a summary of the historical models is given step by step. These maps are shown Figure 8 in section 3.5 where the "master map", summarizing the features taken to be essential for historical models of DC-circuit phenomena, are displayed. Each map concentrates on the phase of concept formation under discussion.

## 5 Results 1: Development of historical models of DC-circuit phenomena

Examining the historical models of DC-circuit phenomena, was the first phase of this design research, see Figure 1. The goal of this phase was to set up the later phases 2 and 3, Design of the learning content, and instruction and evaluation (the teaching experiment at school). This phase gave an answer to the first research question: *How did the historical models of DC-circuit phenomena develop in Volta's time?*

The results were achieved by an inductive content analysis (section 4.4.1) of historical data by emphasising the critical-historical and cognitive-historical views as described in sections 4.4.2 and 4.4.3. The analysis started by reading the historical data several times, picking up the main experiments that Volta used as a basis of conceptualisation of DC-circuit phenomena. These experiments leading to the formation of the historical models and their historical context are described in section 5.1. Thus, the analysis was data-grounded and the development of the historical models was studied through time (horizontality). An important feature of critical-historical analysis, the axis of anachronism vs. diachronism, was realised in a dualistic way: On one hand, the analysis was diachronistic, because the past science was also seen to have a value of its own and its role in the conceptualisation of DC-circuit phenomena was seen to be essential; on the other hand the consensus model of DC-circuit phenomena (see section 6.4) surely helped in searching for the main steps of historical modelling, thus the analysis also had anachronistic and deductive features as well.

In the next phase of the analysis, the modelling process of DC-circuit phenomena was followed by using the tool of analysis, the frame of historical model, designed for the study (3.5, Figure 8). In this analysis, different fragments of the forming models emerged. Every model – a circuit model, an electric fluid model and a model of contact electricity – will be characterised in detail and described as master maps (see sections 5.2, 5.3, and 5.4). Furthermore, the meaning of the models in formation of the basic concepts – an electric circuit, an electric current, and a source voltage– of DC-circuit phenomena will be analysed (5.5). The results of this chapter have been discussed earlier more widely by Kallunki (2001a).

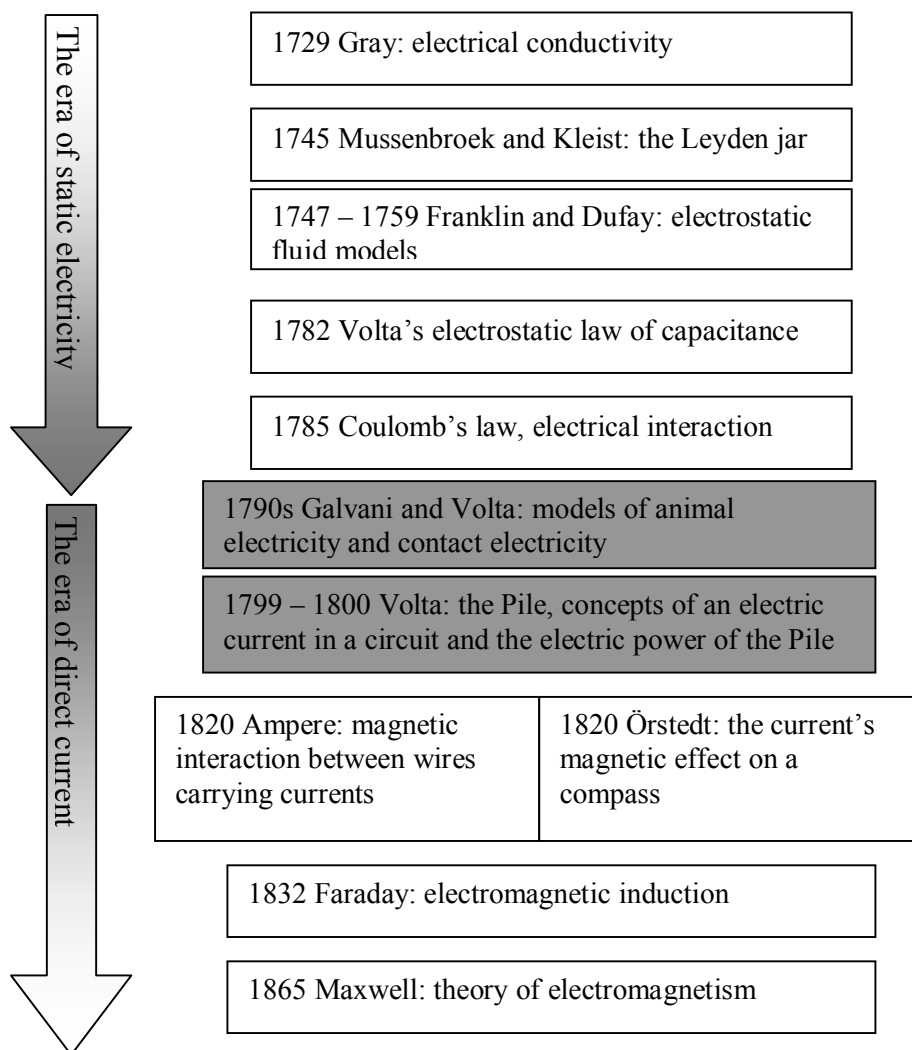
The historical models of the DC-circuit phenomena, especially the model of contact electricity, have been studied earlier from the standpoint of the varying conceptions of the Pile and the combat between Galvani and Volta (Kipnis 2003; Kipnis 2001; Kragh 2000; Kragh 2003). This kind of comprehensive analysis of the development of the models has not however been done earlier.

### 5.1 Empirical basis of the models

The examined processes of modelling DC-circuit phenomena go back to the 1790's to the days of Galvani and Volta. In the 1790's, the study of electricity transferred from electrostatics to the new area of phenomenon, the DC-circuit phenomena. Simultaneously,

very important conceptualisation processes of DC-circuit phenomena took place including the processes of modelling.

For the historical point of view the background is given in Figure 15. It summarises the main turning points of electricity from the early 1700's to the late 1800's. As it can be seen from this chronology the discovery of the Pile in 1799 had a crucial effect on the enlargement of the area of electric phenomena. Before the Pile research into electricity was centred on static electricity and not until the 1790's with the bi-metallic pair, was the first voltage source of electric current constructed. After the Pile research into electricity progressed very rapidly and extended to the area of electromagnetism utilizing the Pile as a generator of the electric current (Humphreys 1937, 164).



**Figure 15** *The chronology of the main turning points of electricity in the 1700's and the 1800's. In this study the focus is on the 1790's and especially in the period of the invention of the Pile, on the work of Volta and Galvani.*

Until the 1790's, the history of concept formation of electrical phenomena was concentrated on the area of electrostatic phenomena. The identification of these phenomena and prequantitative experiments on them date mainly to the 17<sup>th</sup> and 18<sup>th</sup> centuries when the first measuring and collecting instruments of static electricity were constructed. Development of these instruments like the electrical machine to collect static electricity, the electrometer to compare the amounts of static electricity, and the Leyden jar to obtain bigger charges of electricity, was a very important part of the perception process of electrostatics. These instruments helped to figure out and make more definite observations of the properties of electrical entities and electrostatic phenomena. (Kallunki 2000a, 317; Kallunki 2000b)

### **5.1.1 Experiments of electric circuit by the bi-metallic pair**

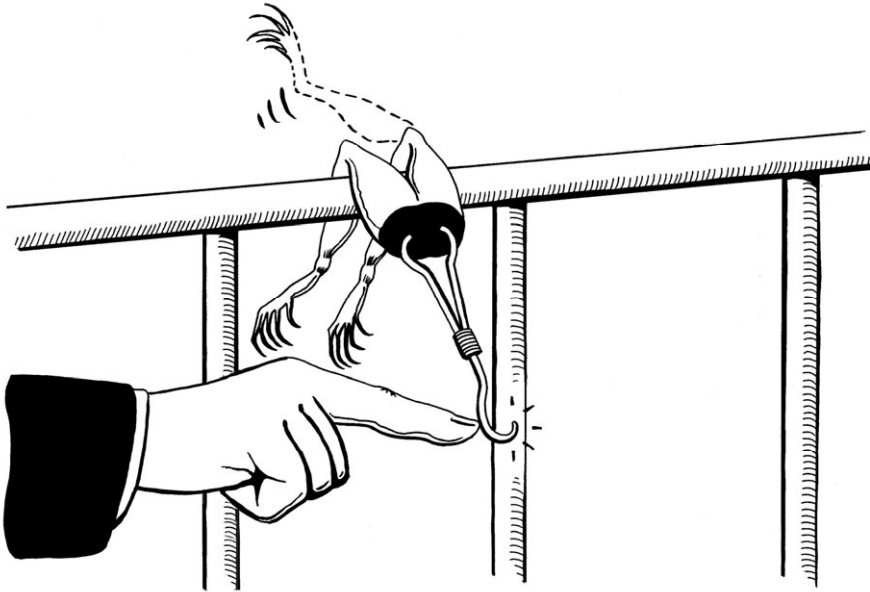
The predecessor of the Pile, the bi-metallic pair, was devised during the modelling debate between Italian researchers Luigi Galvani and Alessandro Volta. The first version of the pair was introduced by Galvani in 1791, and already the next year Volta rose to the challenge, first by repeating Galvani's experiments and then modifying them (Kipnis 2003, 18-19; Kragh, 2000, 134). During the combat, from 1791 to the death of Galvani in 1798, many experiments were carried out as both researchers tried to vindicate their own models of the nature of electricity and its origin. Galvani's model was called the animal electricity model. Volta did not agree with Galvani's arguments and he constructed a contact electricity model to describe his conception. Besides modelling the nature of electricity and its origin, these experiments also widely modelled the closed circuit model (see 5.2).

#### *Galvani's experiments*

Galvani's model was based on the following types of experiments: 1) Leyden jar experiments, 2) railing experiments, and 3) bi-metallic pair experiments. The first version (1780-1781) of his experiments was to apply electric shock to a prepared frog for instance by the Leyden jar (Bresadola 1998, 373-374). When the circuit was closed the muscles of the frog were seen to convulse and contract. The next experiments, which were reported in 1791, did not include an external (known) electrical source anymore. The circuit consisted of the prepared frog, metal pieces and arcs. The so-called railing experiment was described as follows:

...The frogs prepared in the usual manner horizontally over the railing. Their spinal cords were pierced by iron hooks, from which they were suspended. The hooks touched the iron bar. And, lo and behold, the frogs began to display spontaneous, irregular, and frequent movements. If the hook was pressed against the iron surface with a finger, the frog, if at rest, became excited – as often as the hook was pressed in the manner described.

*Pera 1992, 81*



**Figure 16** *The prepared frog over the railing (Pera 1992, 82). Frog's spinal cords were pierced by iron hooks, from which they are suspended. When the hook of the spinal cord touches the iron bar the frog began to convulse.*

Galvani also did bi-metallic pair experiments and in fact repeated the railing experiment with a bi-metallic arc. The new way to do the same experiment was simply to connect the sciatic nerve and the leg of a prepared frog to a bi-metallic arc in order to get the leg to twitch (Kipnis 2003, 18).

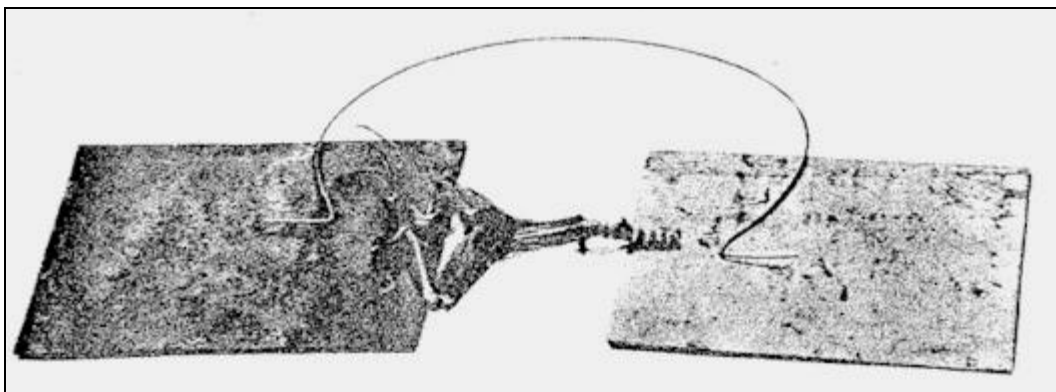
#### *Volta's first experiments against Galvani's model*

Volta noticed Galvani's experiments and especially the way they were explained. Galvani's final conclusions that the animal acts as a source of discharge (Pera 1992, 82) were a starting point to Galvani's and Volta's big controversy on the nature and source of electricity. Galvani's opinion and explanation of the experiments was that animals contain a specific electrical fluid called animal electricity (Pera 1992, 77, 85; Gill 1976, 353). Volta reproduced Galvani's experiments, but after them and his own research, he could not agree with Galvani's model (Gill 1976, 352). Instead, this contradiction was a starting point to his model of contact electricity, which regarded the contact of two different metals as the cause of observed contractions.

In his struggle against Galvani's model, Volta tried different modifications of his circuit. He used circuits, in which two objects of dissimilar metals connected with salt-water liquid or with the prepared frog formed a so called bi-metallic. The goal was to show that the prepared frog was not an essential part of the circuit, but only a sensitive detector of electricity. One attempt was to eliminate the prepared frog from the circuit and replace it with so-called Nicholson's doubler. However, the doubler was known to create its own electricity, so the experiment was not so persuasive (Kipnis 2003, 19-20).

*Volta's experiments with the bi-metallic pair to compare the strength of electromotor of different conductors*

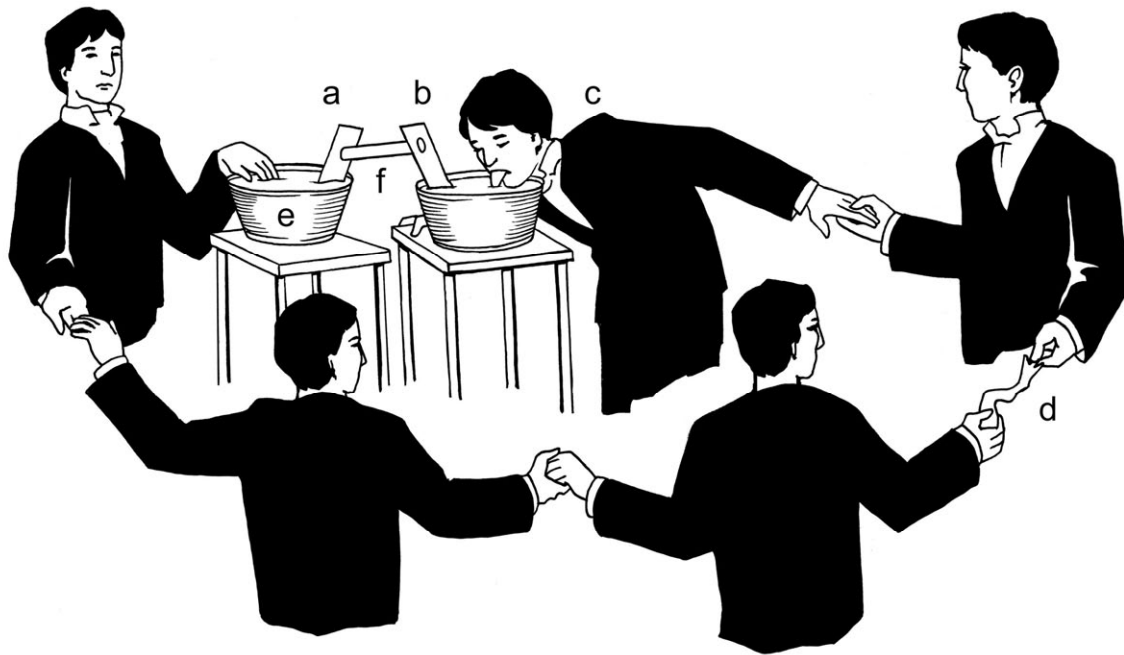
The aim of another series of experiments was to compare the strength of the electromotor of different conductors: bi-metallic pairs, single metals and two second class conductors. According to Volta's modified model, conductors could be classified into two groups: 1) conductors of the first class (metals and some other solids), 2) the second class (liquids or a humid bodies). In these experiments the prepared frog was used as a detector of the electricity: the stronger the contractions the stronger electromotor of the contact. The results were encouraging to Volta: the effects were strongest in the circuit of bi-metals, clearly weaker in the circuit of a single metal and two second class conductors, and only just detectable by very sensitive frogs in circuits of pure second class conductors (Kipnis 2001, 123-124).



**Figure 17** *The frog as a part of Volta's circuit (VO, I: 104). The circuit consists of two different metal disks, which are combined with a metal arc and a prepared frog. In combining the metal disks Galvani used a prepared frog, whereas Volta thought that the connecting part could be any wet body.*

*Taste experiments by the bi-metallic pair*

Volta's so-called taste experiments (1793) are also an important example of bi-metallic pair experiments. In these experiments the equipment was composed of two glasses of water, of which the other included a plate of silver and the other a plate of tin (the bi-metallic Pair). The plates were connected by another metal. The circuit, shown in Figure 18, was a closed chain formed by persons touching each others, and one of them at the end of the chain dipped his tongue into the basin of water (tin), whereas the person at the other end immersed his finger in the other basin of water (silver). (VO, I: 206)



**Figure 18** *Volta's taste experiment. The circuit consists of tin and silver plates (a. and b.), a connecting metal arc (f.), human's tongue (c.), a wet and prepared frog (d.), basins (e.) and a chain of people.*

This kind of connections finally led to the rejection of the body of a frog as a necessary part of a circuit. This also produced proof against Galvani's animal electricity model. As the new invention, the bi-metallic pair, showed that the nerves of an animal were not a source or a cause of electricity, it was time to explain the convulsions in a new way.

### 5.1.2 Invention of the Pile to help experimentations

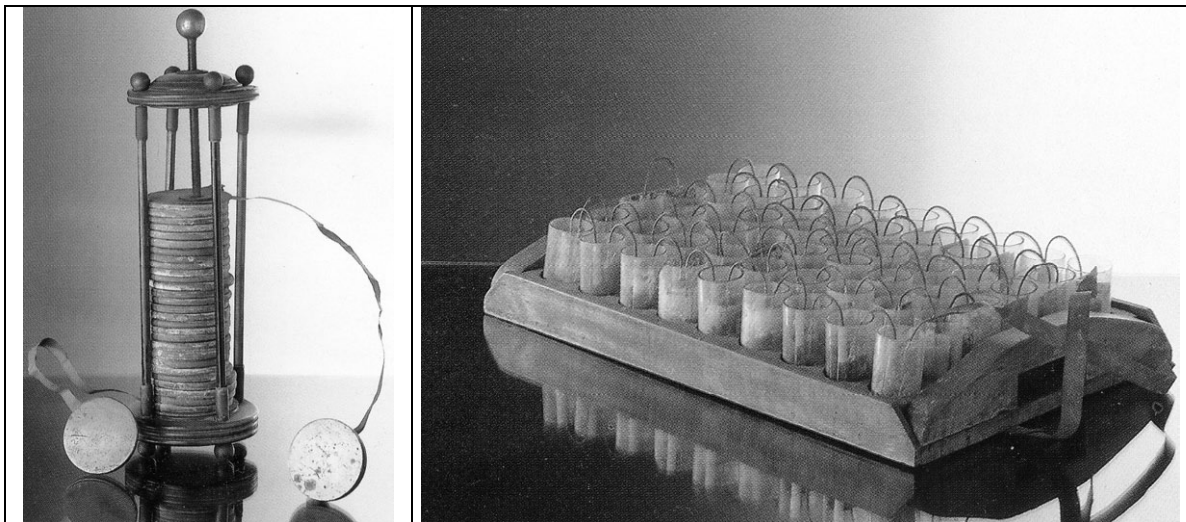
Volta's invention of the Pile was the starting point of DC-circuit phenomena, and thereby to more accurate experiments. The instrument was a simple multifold of the bi-metallic pair. In fact, the origin of its name comes from an Italian word *pila*, which reminds us of the shape of the instrument. The first Piles were column-shaped apparatuses, which consisted of overlapping layers of bi-metallic pairs. The name, the Pile, was taken in use first in the form the Galvanic Pile of Volta and later shortened to the Pile (Davy 1800, 337, 340). The name voltaic pile was also used (Kipnis 2001, 121). The Pile's different names remind us of the concept formation process, which had to be gone through before the instrument could be constructed. Theoretical explanations including the name an electro-motive apparatus (Volta 1800, 302) indicates to the model of contact electricity, which emphasized the role of a bi-metallic pair as a cause of the electrical effects observed in a circuit.

Volta described the structure of the Pile as follows:

The apparatus, to which I allude, and which will, no doubt, astonish you, is only the assemblage of a number of good conductors of different kinds arranged in a certain manner. Thirty, forty, sixty, or more pieces of copper, or rather silver, applied each to a piece of tin, or zinc, which is much better, and as many strata of water, or any other liquid which may be a better conductor, such as salt water, ley, &c. or pieces of pasteboard, skin, &c. well soaked in these liquids; such strata interposed between every pair or combination of two different metals in an alternate series, and always in the same order of these three kinds of conductors, are all that is necessary for constituting my new instrument...

*Volta 1800, 290*

As it becomes evident from Volta's text and from the figure below (Figure 19), the structure of the Pile was very simple. The basic component, two different metal disks and a piece of pasteboard, copper, zinc and wet cardboard, was the same as in the bi-metallic pair. In fact the Pile was just a series of bi-metallic pairs. For a detailed diagram of the Pile see Figure 22 in section 5.1.4.1.



**Figure 19** *Volta's Pile left, and The Chain of cups right (Molteni 1999, 69, 72).*

Actually, Volta constructed two different forms of pairs: the first one was the Pile, the second one was the Chain of cups (Volta 1800, 295), whose mode of operation was the same as for the Pile, but whose structure was a little bit different. In the chain of cups the wet piece of pasteboard was replaced by a non-metallic basin of water filled with salt water. Metal disks in turn were substituted by metal pieces, which were combined together with a metal arc. The idea was actually just the same as that used in the first bi-metallic pair.

What was then the use of the new invention? While the earlier apparatuses had to be charged after each experiment (the Leyden jar) or their electrical signs were too weak for comparative experiments (the bi-metallic Pair), the Pile was able to work continuously i.e. to produce stronger shocks time after time (Volta 1800, 290). Connecting bi-metallic pairs in series bypassed the problem of weak signs of electricity. As the cell voltage of the bi-



metallic pair had been only around 0.75 V (Decker 2005), some indicator had to be used in the circuit. In practise this had meant preserving the frog in the circuits. The new properties of the Pile were very useful in experiments. In Volta's first Piles there were usually 40 or 50 pairs of metal plates (Volta 1800, 302). Other researchers also reported about Piles, which consisted of tens of couples of metal plates (Nicholson 1800, 181). In addition, entire Piles could easily be connected in series to multiply the effects.

### **5.1.3 Experiments of identification, continuity and effects of DC-circuit phenomena in the Pile circuit**

#### *Identification*

The identification of a new phenomenon, an electric current, was based on its effect-phenomena on material bodies, animals and humans. For example, having done the first experiments with the Pile, Volta reported "contractions and spasms in the muscles", "convulsions in the limbs" and sensations of "taste, sight, hearing and feeling" (Volta 1800, 302). Contraction and convulsion phenomena were quite commonly known already in connection with electric discharges. However, the more varied sensations such as taste and hearing became typical only during the phase of studies addressing DC-circuit phenomena.

The Leyden jar and different electrometers were used to identify that the effects produced by the Pile were of electrical origin. Previously, when conceptions of the nature of electricity had been developed, electricity was associated with sparks (shocks) seen in Leyden jars when discharged, and the sparks obtained (electrical shocks received) were identified as electrical. Now the same kind of electrical shocks were received also from the Pile by touching it, and the similarity between the effects was understood as evidence for a similarity between these two areas of phenomena (Volta 1800, 289-290). The similar bases of these two areas of phenomena were also confirmed through other experiments: 1) The Pile was reported to be capable of charging a condenser by contact enabling the condenser to emit sparks. 2) The effects of the Leyden jar were imitated by the Pile by frequently opening and closing the circuit of the Pile by a human body. (Volta 1800, 292) 3) An electrometer was charged by connecting the Pile by a wire to the electrometer. In these experiments the separation between the leaves of the electrometer were taken as evidence of the similarity between static electricity phenomena and DC-circuit phenomena (Nicholson 1800, 182).

#### *Continuity*

Continuity of the DC-circuit phenomena was an important difference between the two areas of phenomena of electrostatics and direct current. This feature of the electric current was so essential that it was addressed already in the first page of Volta's original letter to Banks (Volta 1800, 289). Actually, the continuity was a crucial cause and motive to study this new phenomenon in greater detail. Without continuity there would have been nothing essentially new, but only a new source of electricity – Volta's Pile.

By using the Pile, Volta carried out many experiments based on sensory experiences and sensations. The motive of these numerous experiments was Volta's natural eagerness to vary, generalize and augment the experimental situations and to explore more thoroughly the area of DC-circuit phenomena. On the other hand, his ultimate goal was to find evidence for continuity, which he had identified already in his experiments with the bi-metallic pair, and thus to show the epochal significance of his discovery. In Volta's text the continuity of the DC-circuit phenomenon was described as follows:

The transition of the electric fluid...is not momentary, as a discharge would be, but is permanent, and continues...as long as the communication between the two coatings subsists.

*Walker 1937, 112*

The sensory experiences and the sensation reported by Volta in his experiments with the Pile were numerous and for example he demonstrated that delicate parts of skin, like the forehead, eye-lid or tip of the nose, could feel "a blow and a prick" if connected to a circuit (Volta 1800, 303). In addition the current of electric fluid could be "tasted" because it irritated the sense of taste (Volta 1800, 305). There also were experiments done on the sense of hearing. To do these experiments Volta connected himself to the circuit of the Pile as follows:

I introduced, a considerable way into both ears, two probes or metallic rods with their ends rounded, and I made them to communicate immediately with both extremities of the apparatus.

*Volta 1800, 308*

In these hearing experiments, it was observed that an electrical shock was received at the moment the circuit was closed, and after that was heard a continual sound, "a kind of crackling with shocks" (Volta 1800, 308). This was an entirely different observation than in case of experiments done with Leyden jars, where shocks were instantaneous and no signs of any continuous or persistent effects of electricity were detected. These experiments of Volta clearly focused on the continuity of the DC-circuit phenomena. It was extremely important that the sensations were observed to continue or in some cases even to increase in force until the circuit was opened. This strongly supported the view that the electric current phenomenon itself, behind these effect-phenomena, was also continuous. The same kind of shocks in context of opening and closing the circuit were taken as further evidence of the continuous nature of the phenomenon. (Volta 1800, 303)

#### *Chemical phenomena and the directedness of the electric current*

A new branch of experimentality based on the Pile was rapidly established after the publication of the Pile. For example the Englishmen William Nicholson and Anthony Carlisle studied the observed effects of the electric current in a circuit of the Pile by replacing a common conducting material, a metal, with different kinds of liquids. This

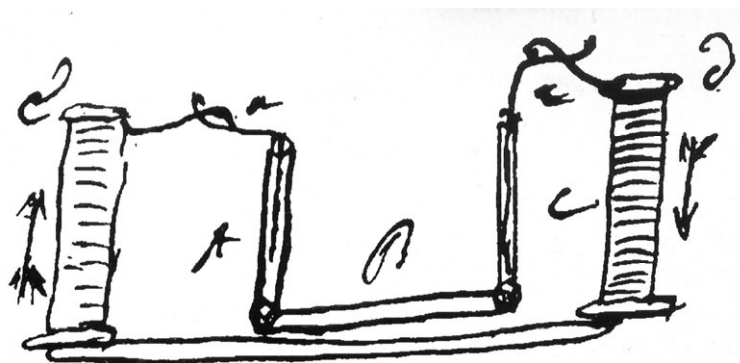
replacement was quite natural, because in many experiments it had been for practical reasons necessary to replace part of a metal conductor with water.

These water experiments revealed a new electric-current phenomenon, "a disengagement of gas round the touching wire" (Nicholson 1800, 182). This new phenomenon was observed and studied with the following equipment:

On the 2d of May we, therefore, inserted a brass wire through each of two corks inserted in a glass tube of half an inch internal diameter. The tube was filled with New river water, and the distance between the points of the wires in the water was one inch and three quarters. This compound discharger was applied so that the external ends of its wire were in contact with the two extreme plates of a pile of thirty-six half crowns with the correspondent pieces of zinc and pasteboard.

*Nicholson 1800, 182*

The above-depicted equipment of Nicholson and Carlisle was described also in Volta's drawing. In Figure 20 there are two Piles connected in series instead of one Pile depicted in a quotation.



**Figure 20** *The Pile and chemical phenomena (VO, II: 329). In this circuit of two Piles (D and E) ABC is the tube of water, A and C are wires of platinum.*

The phenomenon observed in a tube of water was depicted so that "a fine stream of minute bubbles immediately began to flow from the point of the lower wire in the tube" (Nicholson 1800, 182). The new phenomena were identified as a decomposition of water and the formation of a gas (Nicholson 1800, 185). Actually the same chemical reactions were observed to happen also inside the Pile:

It appears that the same process of decomposition of water is carried on between each pair of plates

*Nicholson 1800, 183.*

Also the connection to electricity was clear already from the very beginning:

...a discovery (the Pile) which must for ever remove the doubt whether Galvanism be an electrical phenomenon. But I cannot here look back without some surprise, and observe that the chemical phenomena of Galvanism...

*Nicholson 1800, 181*

Thus these observations expanded the phenomenal area of direct current to the area of chemical reactions. Alongside the chemical actions of the electric current there was also observed an other characteristic of the phenomena of the electric current namely the direction of these phenomena:

A fine stream of minute bubbles immediately began to flow from the point of the lower wire in the tube, which communicated with the silver, and the opposite point of the upper wire became tarnished, first deep orange, and then black. On reverting the tube, the gas came from the other point, which was now lowest, while the upper in its turn became tarnished and black. Reverting the tube again, the phenomena again changed their order.

*Nicholson 1800, 182*

#### **5.1.4 Experiments extending the circuit**

The circuit was extended in two different ways, the first was to add more or bigger Piles to it. The second way to extend the circuit was to increase its length. In the case of Volta the first-mentioned experiments were just the typical experiments with the Pile, whereas the latter were done already before the Pile, with the bi-metallic Pair. Adding the pairs developed the model of contact electricity and the concept of voltage, whereas lengthening the circuit meant developing the model of electric fluid and the concept of an electric current.

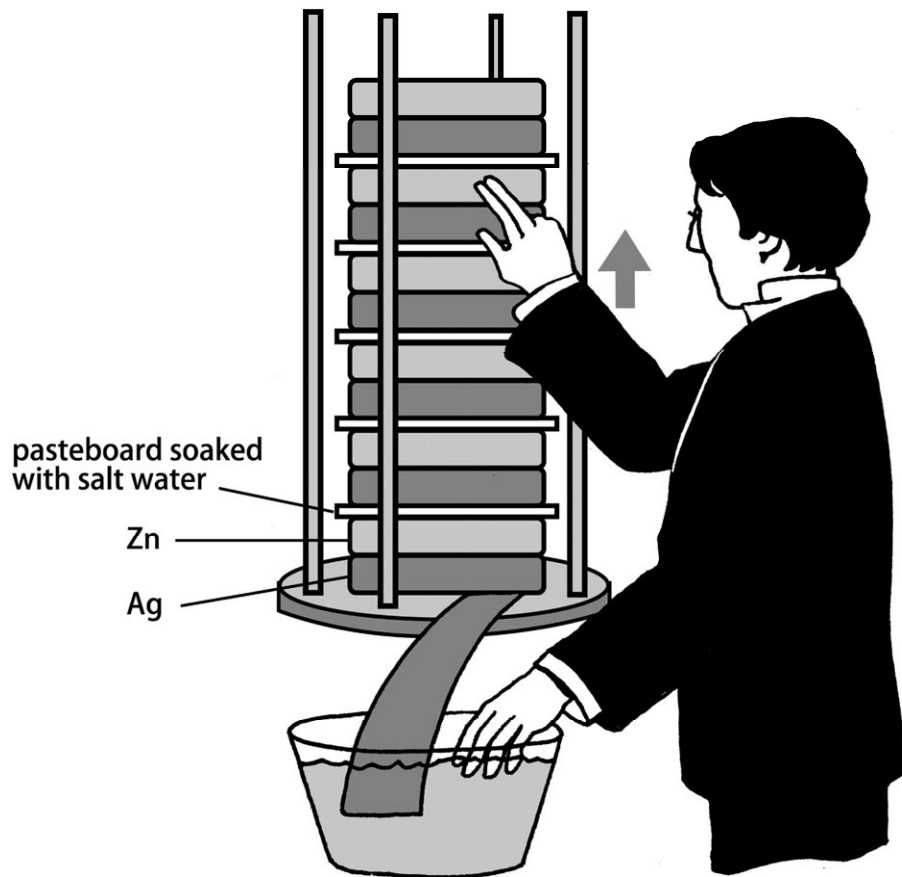
##### **5.1.4.1 More Piles in the circuit – stronger voltage**

Because of its renewed construction Volta's Pile enabled systematic studies concentrating on the strength of effects. It was easy to add components to the Pile and the effects produced were much stronger than those produced by the bi-metallic pair.

In Volta's experiment with a Pile consisting of twenty metallic couples it was observed that a strength of a shock depended on the length of the column in the Pile. If a researcher's one hand touched the bottom of the Pile and the other hand was moved upwards the Pile (see Figure 21), the following observations were made:

By touching then the fifth, the sixth, and the rest of in succession till I come to the last, which forms the head of the column, it is curious to observe how the shocks gradually increase in force.

*Volta 1800, 293*



**Figure 21** *"The shocks gradually increase in force". In this Pile-experiment a person compares the shocks he feels. While holding his left hand on a bottom of the Pile he moves the right hand gradually higher and receives strengthening electrical shocks.*

This observation showed unambiguously that there was a correlation between the number of metallic plates and the strength of the shock received. However, the strength of the electric power was not yet enough for research purposes. To get stronger effects the Pile's column had to be lengthened. By doubling the length of the Pile the effects really increased in force:

...the shocks...will be much stronger, and extend to both arms as far as the shoulder...

*Volta 1800, 294*

...this column, formed of forty or fifty couples of metals, which gives shocks more than moderate to both the arms of one person, is capable of giving sensible shocks also to several persons, holding each other by the hands (sufficiently moist) so as to form an uninterrupted chain.

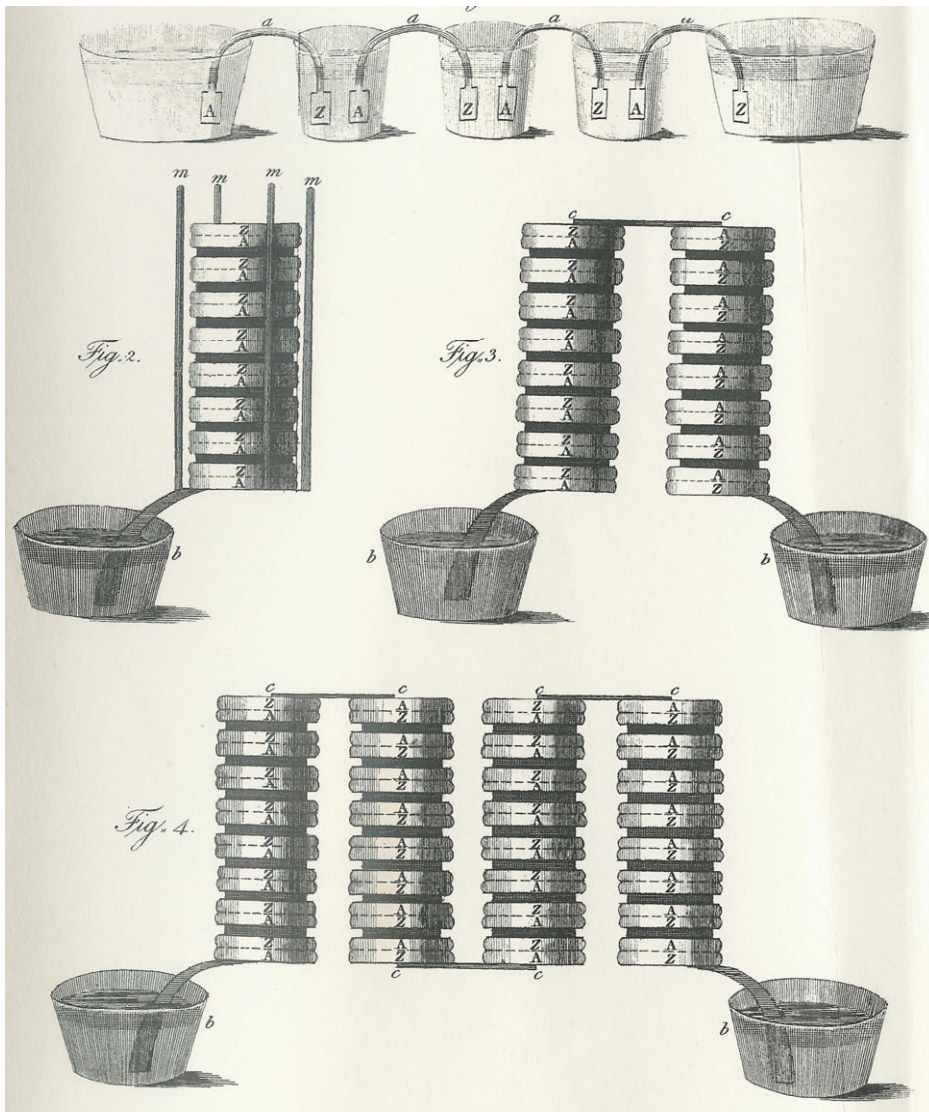
*Volta 1800, 294-295*

Nicholson's article reports more exact results of the strength of the electrical power:

The commotion is stronger the more numerous the pieces. Twenty pieces will give a shock in the arms... One hundred pieces may be felt to the shoulders.

*Nicholson 1800, 180*

Besides the size of a single Pile, there was another way of producing stronger effects. In Volta's picture (see Figure 22) are depicted the idea of adding more Piles in series to increase the electric power of a circuit.



**Figure 22** *Piles in series (Volta 1800), cf. Figure 21.*

With the Chain (the chain of cups, see section 5.1.2, Figure 19) Volta realized the following experimental arrangement, which he used to study the effects resulting from turning around parts of the metal pairs:

Let three twenties of these tumblers be ranged, and connected with each other by metallic arcs, but in such manner, that, for the first twenty, these arcs shall be turned in the same direction; for example, the arm of silver turned to the left, and the arm of zinc to the right; and for the second twenty in a contrary direction, that is to say, the zinc to the left, and the silver to the right: in the last place, for the third twenty, the silver to the left, as is the case in regard to the first.

*Volta 1800, 297*

This kind of arrangement is equivalent to a modern circuit, where some of the batteries in series are connected in reverse polarity. The goal of the experiment was to study how turning around of metal arcs affects the strength of the electric power in a circuit. The experiment was realized so that one hand of a researcher was immersed in the first tumbler of water and with the other one he touched every metallic arc in turn. As a result it was observed that:

...the shocks will gradually increase in force to the twentieth arc, that is to say, to the last of those turned in the same direction; but by proceeding onwards to the 21<sup>st</sup>, 22<sup>rd</sup>, 23<sup>rd</sup>...the shocks will each time become weaker, so that at the 36<sup>th</sup> or 37<sup>th</sup>, they will be imperceptible, and be entirely null at the 40<sup>th</sup>, beyond which...the shocks will be imperceptible to the 44<sup>th</sup> or 45<sup>th</sup> arc; but they will begin to become some sensible, and to increase gradually, in proportion as you advance to the 60<sup>th</sup>, where they will have attained the same force as that of the 20<sup>th</sup> arc.

*Volta 1800, 297-298*

#### *5.1.4.2 Longer circuits – weaker current*

Experiments to compare the strength of the electric current had been done already before the Pile. In fact, the taste-experiments (see Figure 18, section 5.1.1) done with the bi-metallic pair nearly a decade earlier included already a viewpoint of extending the circuit.

##### *Longer circuits by taste-experiments*

Volta reported the results of the taste-experiments as follows:

Experiments of this kind succeed equally well with two, or three, or a greater number of persons, who make a circular chain; only the effects become more weak in proportion as the circuit through which the electric fluid must pass is longer...

*VO, I: 206*

So, the idea of the experiments was to extend the electric circuit, and to study its effect on the strength of the electric current. The tongue of one of the subjects was used as a detector of the electric current, and the strength of the current was studied by varying the number of persons in the circuit. In this experiment the electric current was observed via acid sensations in the tongue and also through convulsions in a prepared frog. The

presence of a frog was necessary because it was the "standard detection device" in most previous investigations on static electricity and thus formed the basis for identification for the similarities of direct current and static electricities.

### *Children's experiments with different lengths of platinum wires*

The most well known systematic research to construct longer circuits and to investigate the effects of the electric current in the circuit of the Pile was carried out by J. G. Children from the year 1808 onwards. For example, in one series of these experiments, platinum wires of different lengths were circuited with Volta's Pile as follows:

Experiment 1. Eighteen inches of platina wire, of 1/30th of an inch diameter, were completely fused in about twenty seconds.

Exp. 2. Three feet of the same wire were heated to a bright red, visible by strong day-light.

Exp. 3. Four feet of the same wire were rendered very hot; but not perceptibly red by day-light. In the dark, it would probably have appeared red throughout.

Exp. 5. On iron wire, of about 1/70th of an inch diameter, the effect was strikingly feeble. It barely fused ten inches, and had not power to ignite three feet.

*Children 1808, 33*

As it appears from the quotation, there were two variables that Children was interested in. The first one was the length of the wire. The second variable was the material (platinum and iron) of the wire. The results obtained were again clear indications of the dependence between the length of the wire and the observed actions of the electric current. However, Children did not comment on this dependence, although from the experimental set-up it is evident that he was aware of the dependency. Instead, his interest focused on those aspects of DC-circuit phenomena, which depended on the differences of the materials. He recognized that the main reason behind different results in heating could be assigned to differences in the conductivity of the materials. Platinum is a "perfect" conductor, so it heats more than iron, which is not so good a conductor. (Children 1808, 34-35)

## **5.2 The model of a closed circuit**

In this section we will summarise the developed *model of closed circuit*. The summary will be done on the grounds of bi-metallic pair experiments depicted in section 5.1.1. Some earlier experiments are also used as a source material. Different fragments of the model will be presented separately. In conclusion the results will be compiled in Figure 23.

The model of closed circuit of electric current has its origin already in the era of static electricity (Kallunki 2001a, 47-48), but the main advances in its development happened



during Galvani's and Volta's controversy. As depicted in section 5.1.1, the original bi-metallic pair experiments functioned as a field for developing the closed circuit model. The model of closed circuit of electric current appeared in Galvani's and Volta's thinking in doing bi-metallic pair experiments. According to Galvani:

There is a kind of circuit of electricity from one part of the animal to the other, which is completed either through an arc or through the water itself functioning as an arc, as the natural philosophers have noticed.

*Pera 1992, 94*

Volta's closed circuit –thinking appears among others in his descriptions of Leyden jar-frog -experiments, which he did to study Galvani's claims of animal electricity:

I then discharge a very feebly charged Leyden jar – that is, exhibiting few or no sparks – over the two armatures placed on the nerve, so that only the nerve segment lying between them is in the circuit of the charge...

*VO, I: 58-60; Pera 1992, 105*

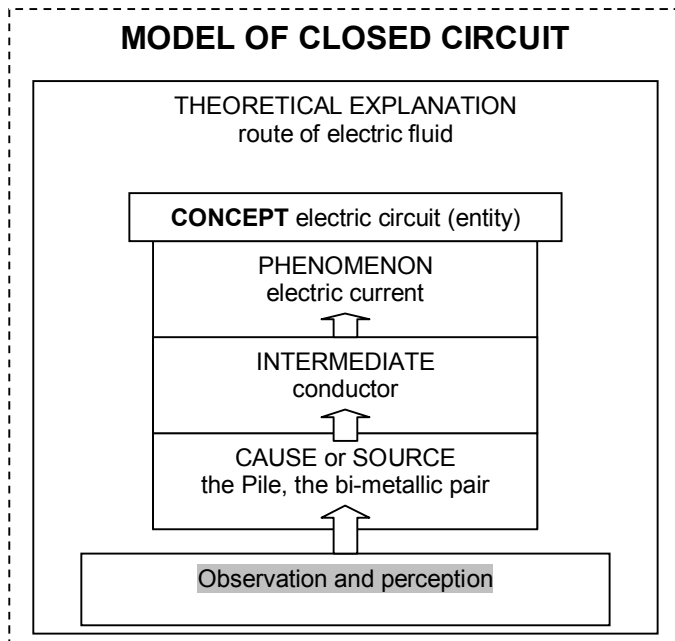
Thus, if it is considered purely technically, it can be said that Volta's circuit was very alike Galvani's. Both of them mentioned the circular path of the electricity (electrical fluid) or charge, which was needed to function as a route of moving electricity. In addition, both scientists needed a source of electricity in their circuits; According to Galvani the source of his circuit was the prepared frog. For Volta the Leyden jar and later the bi-metallic pair or the Pile acted as a source of electricity. In fact, as will be discussed later, Volta understood that the Pile itself is not literally a source of electricity, but it has an ability to move the electric fluid, which naturally exists in metals.

Later in the connection of the Chain of cups experiments Volta still clarified his conceptions about the circuit. Opening the circuit from any place was observed to stop the DC-circuit phenomenon, whereas closing the circuit instantly achieved the phenomenon.

If the chain be in any part interrupted, either by one of the tumblers being empty of water, or one of the metallic arcs being removed or divided into two pieces, you will receive no shock when you immerse your finger into the water of the first and another into that of the last vessel; but you will have it strong or weak, according to circumstances (leaving these fingers immersed), at the moment when the interrupted communication is restored; at the moment when another person shall immerse into the two tumblers, where the arc is wanting, two of his fingers (which will also receive a slight shock), or rather, when he shall immerse the same arc which has been taken away, or any other; and in the case of the arc separated into two pieces, and the moment when these pieces are again brought into mutual contact (in which case the shock will be stronger than in any other); and lastly, in the case of the empty tumbler, at the moment when water poured into it shall rise to the two metallic arms immersed in this cup which before were dry.

*Volta 1800, 298*

Above described experiment also reveals the parts of the circuit in Volta's experiments: the "chain" incorporated essential links like water, metal pair, electric shock, and the people. Thus, the experiment can also be understood as identifying the parts of circuit – a source of electricity, a conductor and a current – that completed the model of closed circuit. The new concept, the electric circuit, described an entity, a scene of the DC-circuit phenomena.



**Figure 23** *Historical model of a closed circuit. According to the figure, the historical model of a closed circuit includes observation-based fragments like parts of circuit – a source (or a cause) of electricity, a conductor and an electric current (phenomenon). These fragments together form the concept, the electric circuit. The theoretical explanation of the closed circuit is the highest level of fragments of the whole historical model.*

### 5.3 The model of an electric fluid

In this section will be summed up the developed *model of electric fluid*. The summary will be done on the grounds of current experiments described in 5.1.4.2. Also some earlier experiments are used as source material. Different fragments of the model will be presented separately. In conclusion the results will be compiled in Figure 24.

### 5.3.1 An electric fluid as a theoretical explanation

#### *Electrified substance*

The model of electric fluid has its very origin in electrostatics (see Figure 15, section 5.1) in the age of Franklin and Dufay (1747 – 1759), and it was based on electrical interaction phenomena. The early observations of electrical phenomena had produced ideas of electrified substance, or essence. Furthermore, ideas of interaction produced by these entities had already taken a form. The corresponding models attempting to give these ideas a more precise form and describe more generally the electrical phenomena were not always purely connected to direct observations, but they were to large degree hypothetical ones. (Kallunki 2001a, 27)

The model of the electric fluid was used as an explanatory device in the connection with research into electrostatics and direct current in 18<sup>th</sup> century. As Volta described at the end of 1770s and 1790:

...an electrical fluid, copiously distributed in bodies to such a degree and in such a manner that all bodies possess it in a quantity commensurate with their capacity.

*VO, IV: 384; Pera 1992, 41*

When does the Electric fluid enter, when does it go out? Which of the two metals gives it to the tongue, which receives it?

*VO, I: 203-204*

In the case of electrostatics, the fluid is described as distributed to bodies and is used as an explanation of electrostatic attraction. The second case of direct current, instead, deals with the first bi-metallic pair, the forerunner of the Pile. In this case the electric fluid is thought also to exist in bodies and to cause electrical phenomena. According the model the electrical fluid was understood as a something entity, which moves as “a package”. This entity could move from one place to another, as it is described in the later quotation.

#### *Two models of an electrical fluid*

In early research into electrostatics, there were two competing conceptions about the electrical fluid. According to Dufay there were two classes of electrical substance while in Franklin’s experiments found only one sort of electricity was found. On the basis of number of electrical groups Dufay’s model was named a two-fluid model and Franklin’s model a single-fluid model. In the phase of concept formation, when the research into the electric-current phenomenon was started there was not any more talk about the contradiction between the two fluid-models. Volta who earlier preferred the single-fluid model (Pera 1992, 160) did not emphasize this aspect in his writings, thought he did always talk about only one fluid, not about two fluids. However it is obvious that it was easier to imagine only one kind of fluid moving in a circuit. Volta’s earlier quotation, “When does the Electric fluid enter, when does it go out?” (VO, I: 203-204) reveals his conception about a single-fluid model. (Kallunki 2001a, 31, 36)

### 5.3.2 Gestalt of an electric current

The name of the model includes a term fluid. This emphasises a gestalt of a mobile microscopic substance. In the phase of the first bi-metallic pair experiments (5.1.1) this motion occurred in a circuit so it was time to depict the path of the motion. Expressions like

...the flow of the electrical fluid... or ...the electrical fluid, which excites and stimulates them by a gentle inflow

*VO, I: 62*

include the new gestalt of the motion of the electric fluid. The terms “flow” or “inflow” stresses the gestalt of a flowing substance, which is “fluid”. This gestalt becomes clearer if the older effluvia models, predecessor of the electric fluid model, are also kept in mind. These models characterized the electrical substance by humid or water-like behaving effluvia particles (Heilbron 1979, 177). Describing the electric current by water analogy is an example of analogical modelling (see section 3.3.1), where the generative principles and constraints for a new model are sought from a source domain.

The model of the flowing electric entity progressed, and the interest begun to shift more towards the phenomenon of flowing itself. Parallel to the term “flow” there appeared the present term “current”, which included the same kind of image of moving liquid or fluid.

...when a current of electrical fluid pervades a muscle...

*VO, I: 62*

...the current of the electric fluid, impelled and excited by such a number and variety of different conductors...

*Volta 1800, 302*

Probably because of the length of the term “the current of the electric fluid” there soon appeared shorter versions like “current of electricity” (Volta 1800, 293) or “electrical current” (VO, I: 58-60). (Kallunki 2001a, 35)

### 5.3.3 Causal connections in the model of an electric fluid

The perception of the causal relations of the DC-circuit phenomena was an essential part of the identification process of the electric current. Questions like, “what is the original causal phenomenon” and “what is only an observed effect of it”, were asked in connection to the Pile. Volta dealt with the problem in the context of identification of the phenomenon (5.1.3) by pondering that

...the current of the electric fluid ...excites not only contractions and spasms in the muscles...it irritates also the organs of taste, sight, hearing, and feeling...

*Volta 1800, 302*

From this one quotation it becomes evident that Volta had understood the gestalt of causal relations of current phenomena. Though the cause-phenomenon, identified as the electric current, had still characteristics of an entity-like acting agent, the effect-phenomena (observed effects) were clearly differentiated from it.

In the identification experiments (5.1.3) different phenomena were discovered like contractions in muscles, convulsions in the limbs, and different sensations and these led to a picture of causal connections in the electric fluid model. Furthermore, Volta's special sensory experiments with his body led to the perception of effect phenomena. In this phase of conceptualisation it was clear that the theoretically explained electric current (or fluid) was the causal phenomenon at the background of the observed effect phenomena.

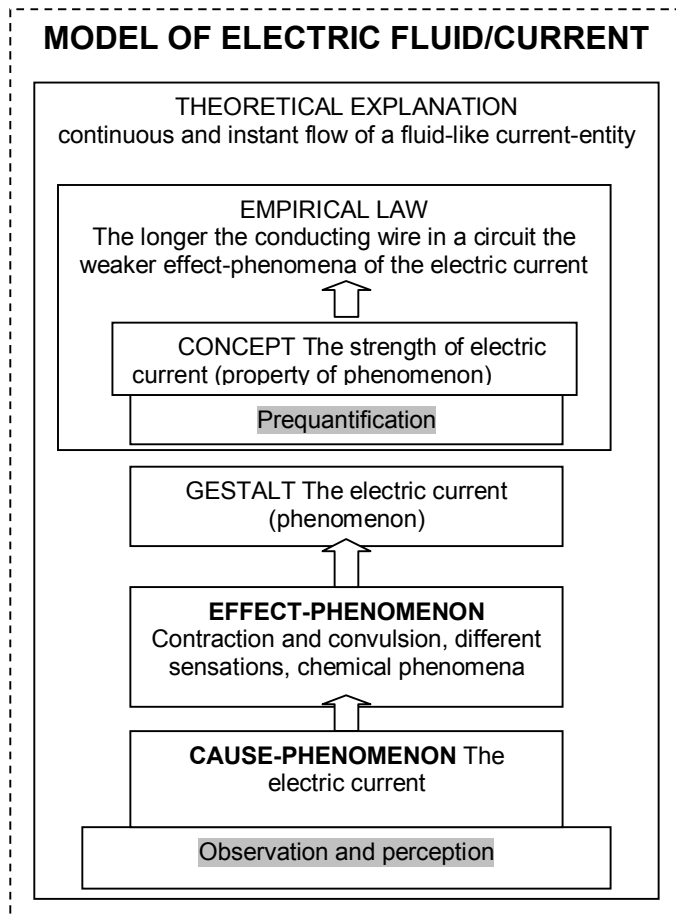
Nicholson's experiments, which found chemical phenomena in the circuit of the Pile were an important achievement in the field of causal connections. For Volta these effects were purely an effect of the electric current rather than its cause (Kipnis 2003, 23). Besides the newly found effect phenomena, they also gave a signal of a certain direction of the electric current. Furthermore, also the identification of the negative and positive poles of the Pile emerged from the same perception process, where identification of the directedness of the current phenomenon became possible.

### **5.3.4 Strength of the electric current and the empirical law**

Volta's taste experiments (5.1.4.2) and Children's platinum experiments acted as tools for defining a new empirical law of the electric current. It was observed in Volta's experiments that the electrical signs weaken, when the circuit gets longer. The same kind of observation was made in Children's experiments, where a comparison was made of the effects on different lengths of platinum wires after twenty seconds in the Pile circuit. The Children's experiments are similar to experiments that increase the number of bulbs in a circuit in series.

The empirical law of the strength of the electric current in Volta's age can be formulated as follows: the longer wire the weaker the effect-phenomena of the electric current. The empirical law of the electric current also defined a new concept, which can be named; the strength of electric current. The new concept described a property of a phenomenon. A level of prequantification was achieved at this phase of conceptualisation, this means that the strength of electric current could be compared, but not yet measured, by sense perceptions.

See Figure 24 below for the detailed historical model of the electric fluid, which describes the conceptions of electric current after the first experiments with Volta's Pile. This model can also be understood as the first consensus model (see section 3.3.2) of the electric current.



**Figure 24** *The historical model of an electric fluid. The model includes observation-based fragments like cause- and effect phenomena, and the fragments of conceptualising phenomenon (the electric-current phenomenon) and its property (the strength of electric current). The model also includes the fragments of the empirical law and the theoretical explanation of the phenomenon.*

## 5.4 The contact electricity model

Volta's *model of contact electricity*, which was introduced in 1792, was one of three rival attempts to explain the function of the Pile and the DC-circuit phenomena observed in its circuit. The competing models concentrated on explaining the causal connections in the circuit: what is the cause of the electric current and what are the effects (Kragh 2003, 42). In spite of intensive competition between rival models, Volta's contact electricity maintained its position of being fully accepted during the first two decades of 19<sup>th</sup> century (Kipnis 2003, 24). Other models presented were Galvani's animal electricity and Wollaston's and Davy's chemical model (Kipnis 2003, 18, 21). The fragments of the model in the form it was introduced by Volta will be described in this chapter.

The chapter will sum up the developed model of contact electricity. The summary will be done on the grounds of experiments done by the bi-metallic pair (5.1.1) and the Pile (5.1.2 - 5.1.4). Different aspects of the model will be presented separately. As a conclusion the results will be compiled in Figure 26.

#### **5.4.1 Causal connections and theoretical explanation of the contact electricity model**

The contact electricity model was used to explain and make understandable the electrical phenomena observed in the experiments of the circuit of bi-metallic pair and the Pile. The following quotation includes Volta's original idea of contact electricity model:

Metals should be regarded no longer as simple conductors, but as a true motors of electricity, for with their mere contact they disrupt the equilibrium of the electrical fluid, remove it from its quiescent, inactive state, shift it, and carry it around.

*Pera 1992, 109-110*

The quotation emphasises an active role for the metal pair in transferring electricity from one place to another. So the metal pair and later also any pair of different conductors (Pera 1992, 112) were identified to have the property of carrying or activating electricity. Volta had varied the metal pairs in his experiments and convinced himself that

it is the dissimilarity of metals that causes it.

*Pera 1992, 108*

By this he meant that he understood a metal pair of dissimilar elements to be the cause of the electric current generated in the circuit.

When Volta's conceptions of the function of the Pile are connected to his ideas of an electrical fluid, the whole chain of causal connections in the circuit of the Pile was completed, i.e., the cause of the electric current is the Pile, or the bi-metallic pair. The role of the Pile appears even from the other name of the Pile; the electromotive apparatus (Volta 1800, 302) emphasizes the Pile as the generator of electricity. As discussed earlier in section 5.3.3, the electric current was understood to be the cause of the effect phenomena observed in the circuit of the Pile. The quotation below includes the Volta's entire train of thought:

The current of the electrical fluid, impelled and excited by such a number and variety of different conductors, silver, zinc, and water, disposed alternately in the manner above described, excites not only contractions and spasms in the muscles...

*Volta 1800, 302*

So it can be concluded that in Volta's model causal relations had two phases:

1. the electrical current was caused by the Pile, and
2. the contractions and spasms are the effects of the electrical current.

The course of events is depicted schematically in Figure 25 below.

QUALITATIVE LEVEL
<i>OBSERVED EFFECT-PHENOMENA</i> Contractions and convulsions Sensations Chemical phenomena
<i>EFFECT-PHENOMENON OR -ENTITY</i> The electric current
<i>CAUSE-ENTITY</i> The Pile

**Figure 25** *Causal relations of the current phenomena as figured out by Volta. Volta's model of causal relations consisted of two phases: The electrical current was caused by the Pile-entity, and contractions and sensations were the effects of the electrical current.*

As the earlier discussed model of electric fluid, the model of contact electricity also includes the idea of a microscopic electrical fluid (see the quotation at the beginning of this chapter), which is normally in an inactive equilibrium state in a metal piece. However, the contact of dissimilar metals disrupts the equilibrium state and affects the DC-circuit phenomena. The quotation emphasises an active role for the metal pair in transferring electricity from one place to an other. Thus, the metal pair and later also any pair of different conductors (Pera 1992, 112) were identified to have the ability to carry or activate electricity.

#### 5.4.2 New property – the electric power of the Pile

The new identified property of the bi-metallic pair was named as an electromotive force or power of the pair. This force was understood to reside “in the contact between two dissimilar metals and a moist body (Pera 1992, 110) or more generally “all conductors of different kinds have an electromotive force generated at their point of contact (Pera 1992, 112).

The property of the electromotive force emphasised the metal pair's ability to get electricity to move. The stress was thereby on the property of a pair of metals, not on a moving entity as in the case of Galvani's animal electricity model (5.1.1). From the standpoint of empirical concept formation this kind of development from an entity to a property is a large step in the process of concept formation. When attention is drawn to real observations it is possible to get more detailed knowledge about the phenomenon. In this case the replacement of a frog by other wet bodies as a part of a circuit enlarged the area of the phenomenon and made it possible to identify the most essential entity of the circuit, the bi-metallic pair. A point to be noted is that this property, the electric power of



the Pile, was particularly meant to characterise a macroscopic entity, whereas the other electric property, the strength of the electric current discussed above, was associated either solely with a phenomenon or to a microscopic entity.

### 5.4.3 Empirical law of electric power

From the very beginning of the research of DC-circuit phenomena, comparative experiments of the electric power property were started. Volta's idea of a comparative property was clear already in connection with the bi-metallic pair:

...with respect to the power of putting in motion the Electric fluid by connection with wet substances; indeed, it rather surpasses gold and silver, so that by making use of tin and charcoal for the two coatings, a greater effect is produced than with Tin and Silver.

*VO, I: 208*

As it appears from the quotation Volta had an idea that by varying the metals of the metal pair also the electrical effects would be greater. So it was concluded that the electric power can be weaker or stronger according to the conductors used (Pancaldi 1993, 285; VO, I: 208; Volta 1800, 294) and "the power of putting in motion the Electric fluid" (VO, I: 208) or "the electric power" (Volta 1800, 294) was found to be a common property of metal pairs. In this context power was evidently used as a description of the strength of the cause, associated with Pile, which resulted in the motion of fluid.

The electric power of a single bi-metallic pair was too weak from the standpoint of research and concept formation. More effective Piles (5.1.4.1) were needed in order to get stronger effects and make experimenting easier. The construction of the Pile was the answer to this problem. In Volta's first Piles there were usually 40 or 50 pairs of metal plates (Volta 1800, 302).

As depicted in section 5.1.4.1 the real Pile experiments were concentrated on adding more and more Piles to the circuit. These experiments confirmed the earlier bi-metallic experiments, and resulted in the same empirical law, which can be formulated as follows: the electric power of the Pile is directly proportional to the number of pairs in the Pile (or number of Piles in the circuit).

Experiments on the Chain (in the end of section 5.1.4.1) confirmed the earlier results of a dependency between the number of metallic plates in the Pile and the strength of the shock. According to Volta the Chain (or the Pile) was an apparatus in which every metal pair had a property to "impel the electric fluid in the same direction" (Volta 1800, 298). So it was concluded that the electric power was an additive property of the Pile or its other versions. Furthermore the quotation also includes a clear model of the circuit's potential, the dependence between the effect-phenomenon and the place in the circuit is apparent. On the other hand the effects resulting from the turn around of the metal pairs were again evidence of the directedness of the DC-circuit phenomena. It is important to note that only through comparative measurements did it become possible to use the physiological sensations as the basis for prequantification.

In this phase, it was perceived that the electric power of a circuit increases if the number of the plates in the Pile or in the Chain is increased. The experiment showed something else about the connection: Inversed metal arcs in a circuit decreased the electric power of the circuit, but equal number of metal pairs connected in opposed directions reversed the electric power. Thus, in this phase the electric power of metal pairs or Piles in series, was understood at a qualitative level of knowledge.

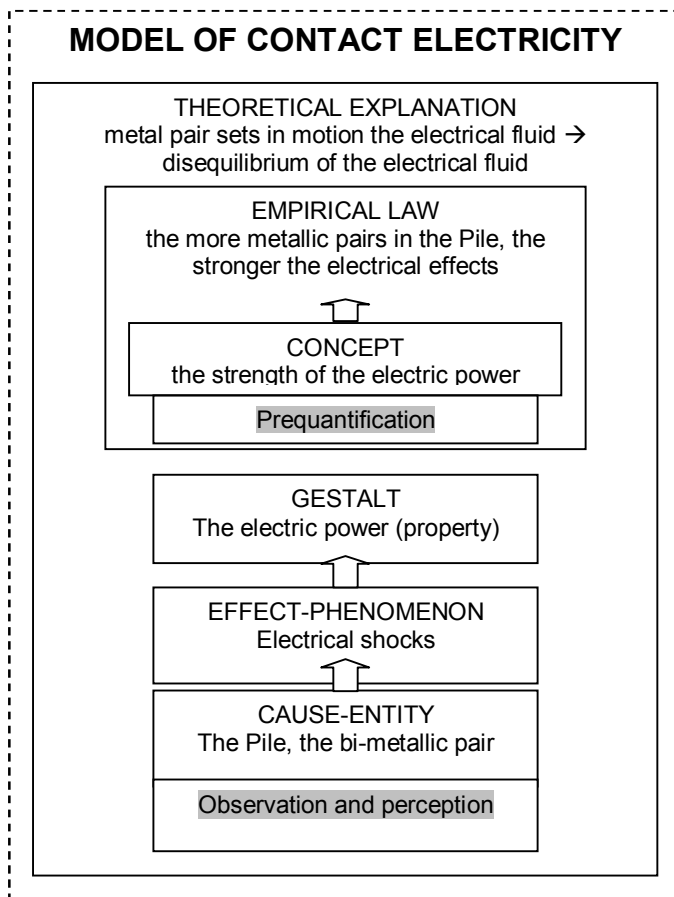
Changing the number of metal pairs or Piles was an external operation to varying the strength of the electric power in a circuit. The other way was to change the inherent properties of the Pile. In the connection of the discovery of the Pile the first idea was to vary the metals in the apparatus. As mentioned above, the idea of different strengths of the electric power in different metal pairs was actually born already in the connection with the bi-metallic pair. Later experiments done by the Pile confirmed earlier observations: different metal pairs have different electric powers (Volta 1800, 294).

Another way to change the electric power of the Pile was to use different liquids between the metal pairs of the Pile. Volta mentioned two alternative liquids of which pure water was worse and salt water better (Volta 1800, 294-295). Davy in turn studied the actions of the electric current more systematically by changing the liquid in the Pile. For example a Pile with muriatic acid as its liquid was observed to be equal in power to a common Pile of seventy plates. Furthermore diluted nitrous acid was even more powerful. (Davy 1800, 342) Investigations done with these modified experimental set-ups confirmed the general conclusions already obtained in Volta's original experiments.

#### *The summing-up of the empirical law of electric power*

The main property of the Pile was the electric power, the predecessor of the source voltage, which was understood to depict a Pile's ability to cause the electric current. In this phase the electric power of the Pile was a concept on the level of prequantitative knowledge, which means that an empirical law was found to depict the dependence between the strength of the electric power and the electrical effect-phenomena. According to this empirical law, adding more metallic pairs to the Pile, or more Piles in series, increases the strength of the electric power. So in this prequantitative phase of the concept formation it was found that there was proportionality between the number of metal pairs and the strength of electric power of the Pile. Also the proportionality between the strength of the electric power of the Pile and the strength of the electric current in a circuit was clear. Furthermore, evidence was found that the strength of the electric power was affected by the choice of metal and liquid used in the construction of the Pile.

Figure 26 shows the contact electricity model. As it appears from the figure, entities and observed phenomena were starting points of conceptualisation. The Pile's property, the electric power, was clarified by prequantifying experiments. The strength of the electric power, described the property of an entity, the Pile or the bi-metallic pair. Moreover, the model of the contact electricity included a causal connection between the cause entity (the Pile) and the effect phenomenon (electrical shocks).



**Figure 26** *The contact electricity model of Volta. The model includes observation-based fragments of cause- and effect-phenomena in the circuit. The fragment, the electric power, describes the property of the Pile. The prequantification includes the fragments of the strength of the electric power and the empirical law, which describes the strength of the electric power. Also this model includes a fragment of the theoretical explanation.*

## 5.5 Picture given by historical models

Until the discovery of the Pile and the first experiments with it, the formation of electric concepts went mainly through the processes of model formation based in perception and prequantification at the qualitative level of knowledge. This resulted in the construction of a qualitative understanding of basic concepts of DC-circuit phenomena. Here the state of perception process at the age of the Pile is discussed from the point of view of the present consensus model of DC-circuit phenomena (see also 6.4). The question is then posed, how electric-current phenomena were understood, and what were the main shortcomings in the network of concepts describing DC-circuit phenomena.

### *Understanding cause- and effect-phenomena*

The observed cause- and effect-phenomena in a circuit were understood through the concepts of the electric circuit and its function. As a result, it was recognized that the circuit consists of three separate parts: the Pile as a source or an activator of electricity, the

wire as a conductor of electricity, and the electric current itself. Although all the three parts of the circuit were understood to be necessary for the system to function, differences in the relative importance of its separate parts were observed. While the role of the wire in a circuit was found to be only transitional, to transfer and express the DC-circuit phenomena, the Pile was instead understood to be the most important part of the circuit. Thus the hierarchy of the parts of the circuit was as follows: The Pile was considered to be the cause-entity, and the electric current to be the primary effect-phenomenon. Light-, magnetic-, heat, and chemical phenomena were thought to be secondary effect-phenomena.

In comparison to modern conceptions of the cause and effect relations in the circuit, the old picture was quite correct in its foundations, but still incomplete. The main shortcomings in the old picture were: 1) the unfinished model of the cause-phenomenon 2) the absence of a concept of electric field, and 3) the lack of a level of concept formation apart from qualitative one. According to the present conception the utmost cause of current phenomena in a circuit of a battery are the electrochemical reactions of the battery. So the picture of the circuit where the Pile was considered the original cause-entity of these phenomena has been later sharpened to those electrochemical reactions inside it.

The three historical models pictured the known DC-circuit phenomena as follows: Electricity is a fluid-like entity, which exists in bodies. This entity starts to move if an external mover excites it. The bi-metallic pair, which consists of two different metals, has a property, the ability to move this electrical entity. The ability is due to the connection of the two different metals, which causes a disequilibrium state to electricity and affects its circulation. Different metal pairs have different kinds of strengths for this ability.

The severe shortcoming in the old picture of the circuit was the lack of the conception of an electric field between the poles of the battery. This part of the concept formation did not happen until the 1810's. However this shortcoming did not prevent understanding the basic DC-circuit phenomena. There is however one thing which the conception of electric field could have affected positively, namely the concept of an electric current, which was still quite much an entity-like concept of the electric circuit not of an electrical state. It is plausible that the concept of an electrical field has later clarified the picture of the electric current as a state of a conductor.

The last shortcoming of the old picture of the cause and effect relations of the circuit was the essentially qualitative stage of the concept formation itself. The concepts remained on the qualitative level mainly because of the technically unsophisticated measuring instruments, which were too inaccurate for really quantitative experiments. So the final definitions of quantities and laws were still without quantitative bases. On the other hand the qualitatively defined concepts included almost all of the information and the meaning content their quantitative counterparts were to acquire afterwards. Thus it can be argued that understanding the meaning of new concepts and ideas was by now means complete, only the possibility to make them more quantitative and precise was limited by the available measuring instruments. In summary, it can be concluded that the historical models explained the observed DC-circuit phenomena on a macroscopic stage and with qualitative concepts.

*State of understanding of the basic concepts*

After the Pile the basic concepts of DC-circuit phenomena, the electric current and the voltage, were thus perceived qualitatively, so the meanings of these concepts were clarified. The two concepts of the electric circuit, the strength of electric current and the electric power of the Pile (forerunners of quantities of the electric current and the source voltage), were then progressed to the stage of prequantitative knowledge. These properties explained the changes in the strengths of electrical phenomena in common connections in series. Thus the effects of adding the number of Piles in a circuit or lengthening the conducting wire could be predicted qualitatively. It was then possible to construct a circuit where the strengths of the phenomena were suitable for a given purpose.

## **6 Design solution: Planning a teaching experiment on the basis of historical models and the corresponding pupil's external representations**

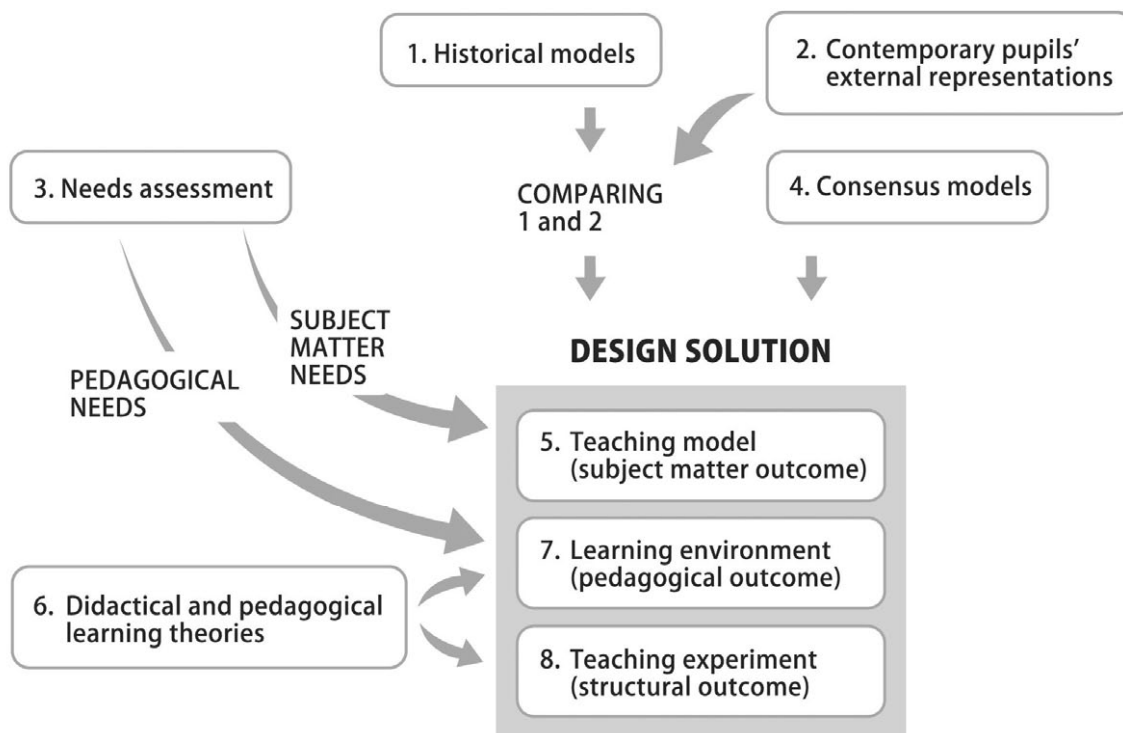
This chapter describes phase 2 of the study, Design of learning content. The factors affecting the design solution, the teaching experiment of DC-circuit phenomena (phase 2) will be depicted. However, the chapter also includes parts of the first phase of the study, namely Finding out pupils' external representations (6.2 and 6.2) and consensus models (6.4), which belong to the analysis of content science, but are closely related to the design process itself (cf. Kallunki and Karhunen 2003). See Figure 1.

Before starting the planning process it is important to survey the needs for a good quality-learning environment. The needs assessment includes both subject matter and pedagogical aspects of the learning environment. This assessing is described in section 6.1.

Furthermore, to start planning the teaching experiment, the research-based information of contemporary pupils' external representations of DC-circuit phenomena is needed (section 6.2). In addition, these representations are compared to historical models (see chapter 5) of DC-circuit phenomena (section 6.2) to see the possible similarities between the two processes of constructing knowledge, and to use this information as a source of innovation for teaching. This comparison is based on the first background assessment, which has been preset in section 1.2.2: Knowledge of the historical concept formation process and historical models can help in planning the teaching of DC-circuit phenomena. Also the examples of resent HPS-based studies discussed in sections 1.6 and 3.3.4 have encouraged searching the similarities of models.

After comparison of models the collected knowledge is used as a new viewpoint for designing the teaching model (subject matter outcome), the talk-activating small group learning environment (pedagogical outcome) and the teaching experiment (structural outcome) (sections 6.5, 6.6, and 6.7) of DC-circuit phenomena. Naturally at the core of the design process are also the generally accepted consensus models of DC-circuit phenomena (see section 6.4).

The design process also includes taking into account didactical and pedagogical learning theories introduced in the theoretical chapters of the study. The didactical learning theories are the approaches of empirical concept formation and modelling, and the new approach, Experimental-centred representation, designed to be based on them (chapter 3 and especially section 3.4). In proportion, the pedagogical learning theories include social aspects of learning like learning in the small group (sections 2.1 and 4.3.2).



**Figure 27** *Summing up the structure of the study from the aspect of the design solution. The figure describes the factors affecting the design process and the artefact itself.*

## 6.1 Needs assessment

One part of setting up the designing work of the teaching experiment was to do a need assessment for a suitable learning environment. A learning environment in this study involves both subject matter and pedagogical issues concerning the empirical part of the research. The needs assessment was done partly on the grounds of the social starting point of the study, the National Curriculum reform, which is described in section 1.2.2, and partially by surveying primary school teachers' opinions (Juuti, Lavonen, Kallunki and Meisalo 2004).

For the needs assessment the opinions of 14 primary school teachers' about physics and physics education were surveyed. Furthermore, based on the survey, three teachers were interviewed to get more information of their expectations for a suitable learning environment. The themes of interviews dealt with difficulties the teachers had had with science content, what kind of reference literature was used or required, pupils' difficulties in learning science, and the most important contents in primary school physics and chemistry. As a result of the needs assessment five different needs were concluded for a learning environment: activating pupils, subject knowledge, easy to use, concreteness and illustration, and support. The needs that could be incorporated in this study are described as follows:

- A. Activating pupils: It was a general expectation that a learning environment should activate pupils. Three different forms of activating needs were found: 1) activate for practical work, 2) activate for thinking, 3) activate for work and study.
- B. Concreteness and illustration: The learning environment should be 1) contextual and from the children's world. This need is close to the pupil activating need. The need emphasises 2) practical work using inexpensive equipment and also the importance of pupils' possibilities to 3) experience physical phenomena (Juuti, Lavonen, Kallunki and Meisalo 2004, 584-586).

How these *pedagogical needs* were answered in this study is described in section 6.6 in the context of realisation of the design solution.

Also the social starting point of the study, the National Curriculum reform, was used as part of the needs assessment. FRAME gives criteria, which define a good performance of physics. These criteria are used here the basis of *subject matter needs* for the teaching experiment. After the fourth grade the electricity-wide subject matter criteria require know-how of connecting up simple electric circuits with a battery, lamp and wires. After the sixth grade of comprehensive school, the pupil's knowledge about electricity is required to be extended as follows: know about different voltage supplies, such as a battery and an accumulator, and know how to do experiments in which electricity is used to produce light, heat and motion. Furthermore, FRAME requires know-how of 1) making observations, 2) describing, comparing, and classifying objects and phenomena, 3) carrying out simple investigations, 4) expressing the acquired information, 5) making measurements, 6) drawing conclusions and for example explaining causal relationships, 7) using concepts, quantities, and their units in describing, comparing, and classifying the properties of substances, objects, and phenomena, and 8) assembling the new information and comparing its correctness on the basis of prior knowledge, investigations, and discussions with others. (FRAME 2004)

## **6.2 Contemporary pupils' representations of DC-circuit phenomena**

The extensive research literature addressing to conceptual learning and of DC-circuit phenomena has revealed many pupils' external representations of DC-circuit phenomena (Gentner and Gentner 1983; Osborne 1983; Kärqvist 1985; Shipstone et al. 1988; McDermott and Shaffer 1992; Borges 1996; Stocklmayer and Treagust 1996; Borges and Gilbert 1999). The models found deal with DC-circuit phenomena, and chart the concepts of the electric current, the source voltage and the electric circuit.

When evaluating child's external representations of the DC-circuit phenomena one's stage of development should be kept in mind is, as this expresses itself as different thinking abilities (see section 2.2.2). Understanding DC-circuit phenomena, which are considered to be quite abstract, possibility requires a stage of formal operations, which the pupils of this study are just reaching. Thus it is understandable that younger pupils' representations are more concrete than those of older ones.



As discussed in section 1.2.1 the target group of this study, 9-11-year-olds, has not been of special interest (Georghiades 2000, 121-122) in science education research. Instead, the focus has been on secondary level students. Thus, the contemporary pupils' external representations described in this chapter are mainly based on research of older pupils than the target group of this study. However, the representations presented here can be used as part of the designing process of the design solution.

Kärrqvist's (1985, 217-220) study found the following external representations of DC-circuit phenomena. The models describe 13-15-year-olds conceptions of the functioning of an electric circuit. The same kinds of external representations had also previously been found in Shipstone's (1984) study of 12-17-year-olds and Osborne and Freyberg's (1985) study of 10-13-year-olds. The following table is based on Kärrqvist's findings, but the main similarities to Shipstone and Osborne and Freyberg are given in the first column.

**Table 7** *Contemporary pupil's models of DC-circuit phenomena according to Kärrqvist 1985, 217-218.*

<b>Name of the model</b>	<b>Description</b>
K1. Unipolar model • Sink model	flow of electric current from the battery to the bulb, only one wire is necessary, with the battery as an agent and the bulb as a receiver, current is transformed into light and heat in the bulb
K2. Two-component model • Clashing currents	two opposite (plus and minus) electric currents meet in the bulb where they produce lighting
K3. Closed circuit model	electric current circulates around the electric circuit and the circuit functions only when it is closed the model is on a technical level
K4. Current consumption model • Sequence model	electric current is consumed as it goes through the circuit, a fraction of current returns to the battery time-dependent model
K5. Constant current source model • Sharing model	the battery always gives the same amount of electric current, two bulbs share the electric current which one bulb would otherwise get
K6. Ohm's model • Scientific view	the electric current is conserved, electric current intensity depends on the appearance of the circuit, the current begins to flow simultaneously all over the circuit when this is closed

The models include conceptual information of pupils' representations of DC-circuit phenomena. The main misunderstanding in the pupils' representations is the *nature of the electric current*: Are there one or two opposite electric currents? Where does the electric current come from? Is the electric current consumed or conserved in the circuit? How does the structure of the circuit affect the electric circuit? Is the electric current some kind of material? Also, the *functions of the electric circuit* and the wire are unclear: Is only one wire enough from the battery? Why does the bulb glow? What happens in the wire when

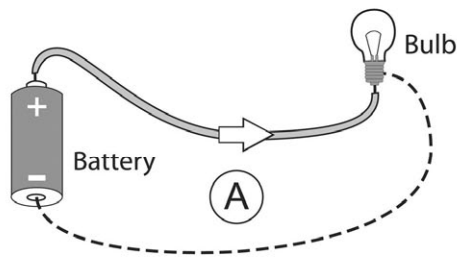
the bulb glows? The *role of the battery varies*: Is it a source of constant electric current, and does the electric current really come from the battery? Where does the electric current come from? What is the relation between the electric current and the source voltage?

Borges and Gilbert's study (1999, 101, 111-112) found that people had four types of mental models (external representations) of DC-circuit phenomena. The models are found from age groups older than 15 including first-year secondary students, third-year secondary students, third-year technical school students, partially schooled practitioners, electrical engineers, and secondary physics teachers. According to Borges and Gilbert (1999) the models evolve in a commensurate manner with the subjects' instruction (see also Nersessian 2002b, 140). This means that the more descriptive models "Electricity as flow" and "Electricity as opposing currents" do not need explicit instruction or experimentation. Therefore, the more scientific models "Electricity as moving charges" and "Electricity as a field" do need instruction and experimentation.

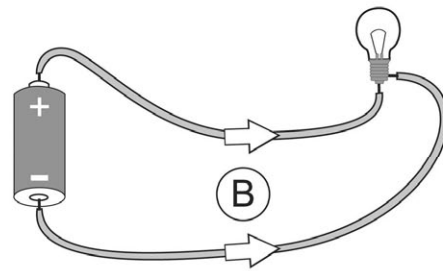
**Table 8** *Pupils' external representations of DC-circuit phenomena according to Borges and Gilbert (1999, 102-107).*

<b>Name of the model</b>	<b>Description</b>	<b>Instructions</b>
BG1. Electricity as a flow  cf. Unipolar or sink model	Electric current as something flowing through the circuit like water in a hydraulic circuit The battery is the source of energy/electricity Energy/electricity as material substance flowing in a circuit	No instruction or experimenting needed
BG2. Electricity as opposing currents  cf. Two-component model or Clashing currents	Electric current and energy used as equivalents Positive and negative currents travel along separate wires, and meet at the bulb to produce heat and light. → non-conservation of current Battery as reservoir of electricity/energy.	No instruction or experimenting needed
BG3. Electricity as moving charges	Electric current consists of electric charges in motion through a conductor The battery as an active source of electricity producing energy, which is delivered to the charges The behaviour of individual components is emphasised, the circuit is not perceived as an interacting system	Instruction or experimenting needed
BG4. Electricity as a field phenomenon  cf. Ohm's model	Electric current is distinguished from energy Electric current as the movement of electrically charged particles under the action of potential difference Electric current circulates in a closed circuit and is conserved, the bipolarity of circuit elements is recognised	Instruction or experimenting needed

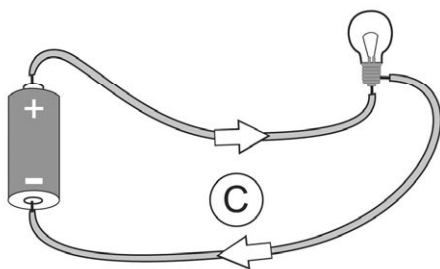
Cosgrove et al.'s (1985) study was on 10-18-year-olds learning the concepts of electric circuit. Pupils' external representations of the DC-circuit phenomena were studied with exercises like those in Figure 28 below. The results of the study showed that the external representations change in relation to age of the pupil; the older the pupils, the more scientific their representations, see Figure 29. This correlation between age and models seems natural and it appears also in Borges' and Gilbert's (1999) models above. The age-model –relationship includes instruction as in both studies the subjects were schooled in physics.



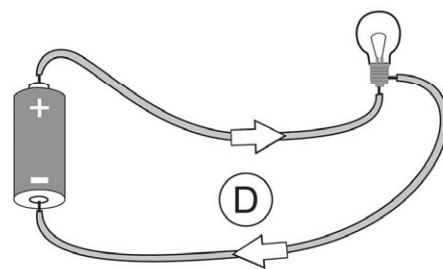
There will be no electric current in the wire attached to the base of the battery.



The electric current will be in a direction toward the bulb in both wires.

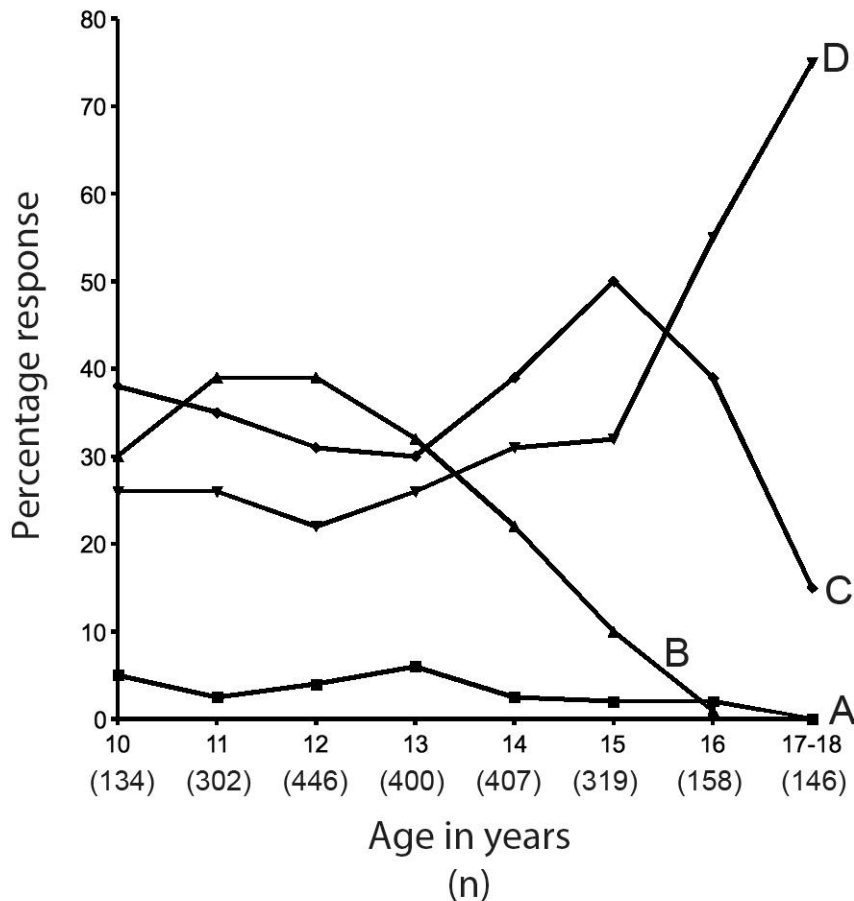


The direction of the electric current will be as shown. The current will be less in the "return" wire.



The direction of the electric current will be as shown. The current will be the same in both wires.

**Figure 28** Which of the alternatives above describes best your representation of the electric current in the circuit? (Cosgrove et al. 1985, 249)



**Figure 29** Variations of popularity of pupils' external representations of DC-circuit phenomena in the age group of 10-18-year-olds. A) Electricity as flow/Unipolar/sink, B) Electricity as opposing currents/two-component/clashing currents model, C) Constant current source/sharing model, D) Ohm's model/scientific model (Cosgrove et al. 1985, 249; Borges and Gilbert (1999, 98-99).

In Cosgrove et al.'s research pupils' external representations were studied in three phases: the first interview was after the pupils had become acquainted with circuits by constructing different electric circuits. The next interview took place just after the pupils had described and argued about their interpretations in the class. The last interviews happened after teaching. Furthermore, the different representations of DC-circuit phenomena were given as alternatives to the pupils. This may have affected the pupils' way of thinking. According to researchers the proportion of model B (Electricity as opposing currents) might increase among younger pupils if the alternatives were not given. (Cosgrove et al. 1985, 248)

On comparing the research frame of this study to the Cosgrove et al.'s frame, the following differences can be seen: in the timing the interviews to chart the pupils' representations, the pupils are younger, the evolution of the representations is tracked also during lessons, and the pupils are not given pat responsive alternatives of the representations. Furthermore, instead of using a current meter in this study bulbs are used

and current strength is inferred from the brightness of the bulbs. In addition the learning environment is designed to be as much as possible pupils' talk activating (see section 6.6).

### **6.3 Comparing historical models and pupils' external representations of DC-circuit phenomena**

Both historical models and pupils' external representations of the DC-circuit phenomena are basically qualitative and descriptive explanations of observed phenomena. These models are also based on the same kinds of simple circuit experiments like constructing a circuit, adding more batteries to the circuit, lengthening the circuit somehow, or changing the circuit in some other way. Pupils' representations are based on everyday life observations and school learning, whereas the historical models were based on systematic empirical experiments (see section 5).

In this chapter the similarities and differences of the pupils' representations and historical models of DC-circuit phenomena will be discussed. The comparisons will be done on the basis of descriptions given in the context of pupils' representations (Kärrqvist 1985; Borges and Gilbert 1999) and historical models (chapter 5). However, the information used is not comparable in every way. The studies reporting pupils' representations generally are concentrated on causal connections, identified properties, and theoretically orientated explanations of DC-circuit properties. They do not include information on comparative properties or empirical laws, which play an important part in the historical models. Thus, the comparisons are made only when applicable.

#### *Electric current like a substance*

Borges' and Gilbert's first model (BG1) "Electricity as flow" defines electric current as a flowing material substance, which moves in the circuit like water in a hydraulic circuit. This model is according to Borges and Gilbert particularly popular among children, who have not schooled yet. The same representation also appears in Kärrqvist's classification in the Unipolar model (K1). Furthermore, a substance-like picture of electric current can be seen in the models of K2 and BG2.

These pupils' representations include a picture of the electric current, which is very similar to Volta's historical model of an electric fluid. As discussed in section 5.3 the historical model of electric fluid includes a conception of an electrified substance, which moves as "a package" in the circuit.

Volta's model of electric fluid also speaks about the number of existing fluids or electric current. The model supports the old controversy of a one-fluid model against a two-fluid model. In this respect pupils' representation of two opposing currents, which appear in many studies and has been called the "two-component model" (Clashing currents, Electricity as opposing currents), is very natural. The step from a two-component model to one single electric current can be seen as part of the evolution of an external representation for electric current.

In the historical model of electric fluid an understanding of the instant nature of the phenomenon is very clear. The electric current is understood to be generated instantly all

over the circuit. This conception may not be obvious in pupils' representations, except in K6 the highest level of models. Thinking according to representations K1, K2, K4 or K5 (or BG1, BG2) may lead a pupil to the incorrect conclusion that the substance-like electric fluid does not arrive simultaneously at different parts of the circuit, but in chronological sequences as it is represented in K5.

In respect to the nature of the electric current the theoretical explanation of the phenomenon the representations of pupils and historical models are close. Though Volta's representations are much more developed in many other aspects of the DC-circuit phenomena his theoretical explanations bear close similarities to the pupils' representations. On the other hand, it is very understandable that at the beginning of the era of DC-circuit phenomena, there were so many views to think about them that all fields could not evolve at the same speed.

#### *Causal connections between the electric current and its effects*

At least models K1 and K2 offer information of pupils' representations concerning the causal connections between the electric current and effects observed. In pupils' representations the electric current is either transformed into light and heat in a bulb (K1) or produced by two electric currents in a bulb (K2). In addition, model BG2 describes the heat and light produced when positive and negative currents meet at the bulb.

According to Volta's historical model of electric fluid (see 5.3.3) the electric current causes observed effect phenomena like contractions and convulsions, different sensations and chemical phenomena. In this phase the historical model does not comment exactly on the process of the effect phenomena: the electric current just excites the effects observed.

#### *Modelling an electric circuit*

The representations of the electric circuit vary in pupils' different models: the K1 electric circuit is the most incomplete regarding only one wire for the electric current. K2 requires two wires, one for each current, and the circulation of the current is not included. The K3-K6 models understand that a closed circuit is a necessity for DC-circuit phenomena: in K3 the stress is on the technical level of model and all that really means is the need to find the closed circuit. The K4 model sees the circuit in an atomistic way looking at the parts of the circuit piece by piece, whereas K5 understands the circuit partly in a holistic way emphasising the need for sharing the current. According to K5 the current strength is the same all over the circuit except for the bulbs.

In the historical model of the closed circuit the circulation of the electric current is clear. Also, the different components of the circuit are seen to be necessary. The circuit is understood as a path or route for the phenomenon, and the model emphasises that all the components are needed in the circuit. In the pupils' representations the roles of different components of the circuit are not so obvious, not battery is understood to be an important component of the circuit. However, the utilities of the wire and the circular path of the electric current are unclear, this can be seen in the different versions of the required number of wires, as discussed above.

The distinguishing point of historical models and described pupils' external representations is in underlining the components of the circuit in the historical model. The

historical model includes a clear picture of the meaning of different parts of the circuit, whereas in the pupils' models the meanings are weaker.

As frequently reported (1.2.1) students often have a tendency to think of a circuit more locally than as a whole. Model K4 is a clear example of an atomistic representation: the parts of the circuit are looked at piece by piece, not as a whole. In contrast, model K5, includes quite a holistic way of representation. The circuit is seen as a system, which shares the electric current. There exists however a discontinuation point in K5, because the flow of electric current is understood to take place in chronological sequences.

There is also discontinuation in Volta's historical model of the electric circuit. Although the electric current is understood to be generated simultaneously in different parts of the circuit, the flow of the current is however thought of locally: In Volta's representation there is a clear picture of the electric current, which transfers as a package and arrives after a while at another part of the circuit. This is an example of a stage of conceptualisation when the model used is not comprehensive yet, but there are properties in the model, which are inconsistent with each other.

#### *The model of source voltage and battery*

It can be said that in the most of pupils' external representations the meaning of the battery is little overemphasised as the most important part of the circuit. Like Volta, pupils understand the battery as a cause of the current phenomena, but in their models current is too closely linked to the battery. Many pupils think that the battery is a store of current, not a generator of it (K1 and BG1). Moreover according to K5, the battery is a constant current source.

Contrary to pupils' external representations of the functioning of the battery, the historical contact electricity model clearly attributes the electric-current phenomenon to the contact of two dissimilar metals, and the role of battery as a electromotive agent instead of its store.

From the standpoint of the causal connections of the whole system, the electric circuit, pupils' representations and historical models have similarities and differences. They are similar to the direction of the cause and effect chain, the cause is in the battery and the effect is in a bulb. According to pupils' representations the battery is a source and the bulb is a receiver (K1, BG1, BG2, K2, K3), whereas the historical model of contact electricity regards the battery as a mover of the electric current and the light of the bulb to be an effect phenomenon of the electric current.

#### *Current strength and magnitude of source voltage in models*

Contrary to historical models of electric current and source voltage, in reported pupils' representations of DC-circuit phenomena there are no reported results of pupils' representations of magnitudes for the electric current or magnitude for the source voltage.

In summary, it can be concluded that there are similarities between pupils' external representations and historical models of DC-circuit phenomena. These similarities show that ways of thinking in science and learning are at least partially parallel, so the historical models of DC-circuit phenomena can really be used as sources of innovation for teaching electricity at school.

## 6.4 Consensus model of DC-circuit phenomena

The conceptions of DC-circuit phenomena represented at a university level foundation course for physics pupils can be considered as a consensus model (cf. model categories in section 3.3.2) of the subject matter. As discussed earlier the consensus model stands for generally accepted conceptions of the subject matter, which have been published. In this way they represent the existing conception of the field of research. The parts of the consensus model of DC-circuit phenomena, which describe the subject matter at a qualitative level, from the standpoints of basic properties are presented in this section. The content of the model is limited just to basic concepts to fit to the following teaching model of comprehensive school's lower stage graders, thus it concentrates on the qualitative level knowledge structure of DC-circuit phenomena.

### *Basic components of DC-circuit phenomena*

The system of DC-circuit phenomena consists of electric current itself, a current source, and a wire, forming an electric circuit, the basic environment for the phenomena. The simplest version of the electric circuit is a closed loop of the wire, in which the terminals of the current source are connected. The current source is an active component: the current-source phenomenon is the cause of electric current. Therefore, the role of the wire is to be a passive component, it offers only a place for the phenomenon. The electric current is understood to be a phenomenon, which takes place in the circuit. (Kurki-Suonio and Kurki-Suonio 1993, 141-142)

### *Electric current*

The electric-current phenomenon is identified by its observed effects. One sees the effects: thermal, magnetic, and chemical. An electric current also has direction, which can be seen by observing the chemical or magnetic effects.

The electric current has strength, which is manifested by its effects. These effects are used as a basis for measurements: the electric current is understood to be the stronger 1) by the larger magnetic forces from the wires interacting with each other, 2) the faster the chemical reactions happen, or 3) by the more the wire heats up. The quantity describing current strength is the electric current ( $I$ ), and its definition is based on the magnetic forces between the wires. The electric current is the same all around the unbranched electric circuit; at any moment there is an equal electric current going through every cross-sectional area of the wire. Moreover, electric current is generated and switched off simultaneously everywhere in the circuit. (Kurki-Suonio and Kurki-Suonio 1993, 142-153)

According to the theoretical explanation of an electric current the movement of the wire's charged particles causes the phenomenon. There exists also a general explanation of electric current; the phenomenon is the effect of an electric field. (Kurki-Suonio and Kurki-Suonio 1993, 151, 153)



### *Source voltage*

The current-source phenomenon generates electric current. These phenomena are in fact inverse phenomena of the electric current effects, only the direction of the reaction changes. The electric-current phenomenon can be generated by mechanical-, thermal- or chemical means. Furthermore, from the standpoint of the electric field, the current-source phenomenon maintains the electric field of the wire. (Kurki-Suonio and Kurki-Suonio 1993, 153-154)

The current-source phenomenon has strength, which is defined by quantity, a source voltage ( $E$ ). The quantity is a characteristic of the element's chemical reaction, and it manifests the strength of current-source phenomenon. The source voltage of a battery determines the magnitude and the direction of the electric current,  $I = I(E)$ . When the electric circuit is closed, an electric current is instantly generated in the circuit, which remains unchanged until the current-source phenomenon starts to drain.

Then there is a voltage drop in the wire. The potential of the electric field is at its highest level in the positive terminal of the current source, and decreases towards the negative terminal. The voltage between two points of the wire is called as a voltage drop  $U_{AB} = V(A) - V(B)$ . (Kurki-Suonio and Kurki-Suonio 1993, 156)

## **6.5 Subject matter outcome – teaching model of DC-circuit phenomena**

In this section we will discuss the outcome of the above-depicted subject matter designing process, the teaching model used in this study. As was stated in the preface of chapter 6 (see Figure 27), the teaching model of DC-circuit phenomena used in the design solution will be designed on the basis of historical models, contemporary pupils' representations, a needs assessment and consensus models.

Table 9 sums up the main subject matter factors used in generating the teaching model of DC-circuit phenomena. The table describes the teaching model from the standpoints of the electric circuit, the electric current and the source voltage. The table emphasises the main characteristics of each factor while trying to avoid overlaps. This means that every idea is mentioned only in its main context.

**Table 9** *The main subject matter factors used in generating the teaching model of DC-circuit phenomena. The pedagogical solutions on the grounds of pedagogical needs will be described in sections 6.6 and 6.7.*

<b>Concept to be modelled</b>	<b>Ideas from historical models of DC-circuit phenomena</b>	<b>Ideas from needs assessment (subject matter needs)</b>	<b>Ideas from pupils' external representations</b>	<b>Ideas from consensus models</b>
Electric circuit	Emphasising the role of a circuit in modelling, the circuit as a crucial concept. Components of the circuit, the meaning of every component The circuit as a route of electric current	Know-how of connecting up simple electric circuits with a battery, lamp and wires	The circuit as a whole instead of local understanding. How to impact on: 1. Unipolar model (one wire) → the structure of the circuit Bulbs as parts of a circuit → structure of a bulb	The current source as an active component: the current-source phenomenon is the cause of the electric current. The role of wire is passive.
Electric current	Instantaneous electric-current phenomena Continuous electric-current phenomenon Electric current a cause phenomenon → contractions effect phenomena Electric current as a property of phenomenon Comparing current strength by lengthening the circuit Empirical law: the longer wire in a circuit the weaker effect-phenomena of the electric current (the weaker electric current)	Know how to do experiments in which electricity is used to produce light, heat and motion	How to impact on: 1. "Electricity as flow" representation? → To do observations of instantaneous electric-current phenomena. 2. "Two-component" representation? → To add more bulbs to the circuit, and put children to explain the situation. 3. Battery as a constant current source → To compare the brightness of the bulbs 4. Current consumption → to compare the brightness of the bulbs 5. Constant current source → To vary the number of bulbs and compare the brightness of them.	The electric current is the stronger the bigger effect phenomena are.

Source voltage	Battery/Pile as a cause entity, electromotive agent → Electric current as an effect phenomenon → Contractions, sensations and chemical phenomena as observed effect-phenomena Electromotive force as a property of a battery (entity) Comparing magnitude of the electromotive force by adding more batteries in series	Know about different voltage supplies, such as a battery and an accumulator	How to impact on representation of “battery as a store of electric current”? → To observe the instantaneous current phenomena, to learn the concept of a closed circuit	Current-source phenomenon generates the electric current. The source voltage determines the magnitude and the direction of the electric current. The potential of the electric field is at its highest level in the positive terminal of the current source, and decreases towards the negative terminal. The electric field as a general explanation of the electric current. → Does not appear in historical model, and will not be used in the design solution.
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On the grounds of the analysis of factors described in Table 9, the teaching model of DC-circuit phenomena was planned to include many experiments focusing on black spots of learning and applying the ideas of concept formation processes of historical models of DC-circuit phenomena.

The teaching model dictated that the concepts of the electric circuit and the electric current should be taught first in a joint fashion so that they supported each other. It was decided to teach the concept of a source voltage after them. The designed subject matter teaching model was as follows:

*Teaching model of the electric circuit and the electric current*

Teaching of DC-circuit phenomena starts by identifying the parts of the electric circuit. The different parts are named and the structure of the circuit is emphasised. The battery is understood as a cause entity of the electric-current (effect phenomenon), the conducting wire is understood as a connecting and closing element of the circuit. Also, the structure of the bulb as a part of the circuit is highlighted. Moreover, the poles of the battery are underlined to underpin the concept of the electric circuit.

The electric current is generated in the electric circuit, which can be observed by the instantaneous lighting of the bulbs. The electric current can be measured by comparing the brightness of the bulbs. The electric current in the circuit depends of the number of bulbs in series: the more bulbs the smaller the electric current. At the same time it can be observed that every similar bulb shines as bright as the others, which also tells us that the

electric current is similar at every point of the circuit. The electric current does not exist without the battery.

#### *Teaching model for the source voltage*

When connecting batteries in series the same battery has the same source voltage even when the number of bulbs in the circuit is changed. The number of batteries can be used as a measure of the source voltage. By adding more batteries in series it can be seen that the source voltage increases, because a single bulb in the circuit shines brighter.

The battery has the property to cause the electric-current phenomenon, thus the electric current is an effect phenomenon of the source voltage. Using the number of batteries as a gauge of the source voltage the concept of source voltage is fixed to a property of the battery. Respectively, the electric current is perceived as a phenomenon, which depends on the bulbs in series.

#### *Conclusion of the teaching model*

The teaching model is a mixture of utilising historical models, leaning on the needs assessment, taking into account pupils' external representations, and bearing in mind existing consensus models of DC-circuit phenomena.

Innovative in the designed teaching model is par excellence the use of historical models of DC-circuit phenomena. As summed up in Table 9, the role of historical models is to act as a main source for ideas of DC-circuit phenomena and their properties by comparing experiments. Furthermore, the stress of the concept of the electric circuit originates from its essential role in the historical concept formation process. In addition, the causal relations of DC-circuit phenomena proposed in the historical models are easy to apply to the teaching models. In generally, what the utilisation of the historical models of DC-circuit phenomena offers is the ability to focus on perceiving experiments as a crucial part of conceptualisation, and the language used as an indicator of modelling process.

## **6.6 Pedagogical outcome – the talk-activating small group learning environment**

The other side of the design solution consists of pedagogical aspects of learning. The aim in designing is to construct a learning environment, which takes into account 1) the pedagogical needs (6.1) and 2) the pedagogical theoretical background described in chapter 2 and section 3.3. According to these views a suitable learning environment readies pupils for practical work, thinking and studying. Furthermore, the learning environment is contextual and from the children's world also including practical work and experiences of physical phenomena.

In the design solution, the purpose is to organise the pupils by activating their learning environment to promote the learning of DC-circuit phenomena and to make learning as visible as possible. The goal is to uncover pupils' external representations, challenge the earlier external representations, and generally promote the learning processes of DC-

circuit phenomena. Thus the meaning of the language used and the talk engaged in are important keys to the learning process. According to the approach of learning adopted in this study (3.4) both empiricism and earlier external representations are essential factors in learning. Thus, various paths can be traced such as: 1) language – concept formation/modelling 2) experimentalism – concept formation/modelling and 3) talk – active learning – challenging earlier external representations – concept formation/modelling, which all point to a possible design solution: talk-activating small group learning environment. This kind of design solution also supports the aim of operationalising external representations as described in section 3.3.3.

In order to facilitate these aims the study uses different talk-activating tools. Section 4.3.2 put forward reasons for applying small-group learning such as its usefulness to affect pupils learning positively through discussions and negotiations. It also was argued that group discussions challenge pupils' earlier external representations. Section 3.3.3 put forward possible ways of operationalising external representations like thinking-aloud, problem-solving tasks, and making explanations and predictions. Thus, this study uses small group learning as a basis for a talk-activating learning environment and adds some activating tools to increase talk and learning.

One approach for proposed for activating young children's learning in a small group is to use plays and games, which are a natural way of processing things for this age group. As activating tools, along with the small group work itself, we use connection cards, claim cards, word explanation, dollhouse electrification, and solving the problem of a broken pocket lamp.

#### *Claim-card competition*

Claim cards are used at end of the third lesson, just before the intermediate interview. The point of the cards is that they include claims and drawings about the electric circuit. After reading a claim the pupils individual think about them and writes down a "true" or "false" answer. When every one is ready, the claims are explained in turn. The claims are described in Appendix 2: Claim cards

#### *Word-explanation game*

The word-explanation game is part of the design solution's final interview, in which the idea is to explain given DC-circuit phenomena related words to other small group members without mentioning the word or part of it. One group member explains and the others try to guess the right word. When every small group member has found the word, she/he tells it to the teacher. If any of the words are not right or only partially right, the teacher asks for more added explanations. The pupils are naturally very keen on playing this kind of game, so this is a good chance to get lots of talk about the subject matter. The words to be explained are: the wire, the electric circuit, the voltage, the electric current, the battery, the closed circuit, the bulb, 9.0 V, and the terminals of the bulb.

#### *Dollhouse electrification and problem of a broken pocket lamp*

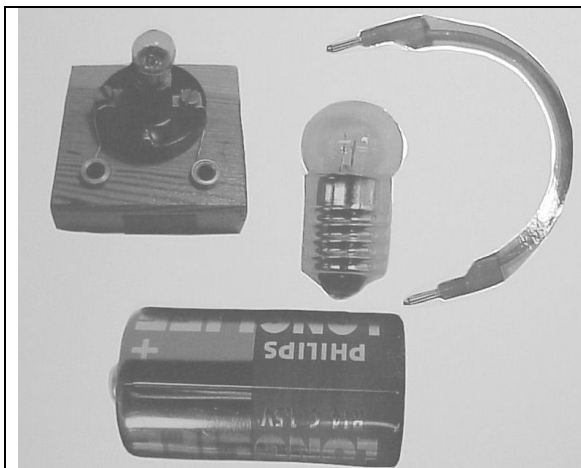
The dollhouse electrification is a task planned for the end of the teaching experiment. The small group gets an open problem-solving task to plan the lights of the dollhouse. The

directions include the ground plan of the house including places for different kinds of lights: for instance, the bulb on the writing desk should be very bright, whereas the three bulbs in the headboard should be dim.

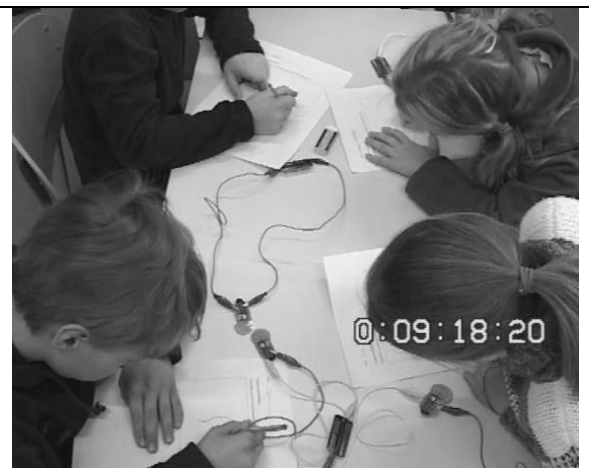
The other problem-solving task is the problem of a broken pocket lamp. There are several lamps on a table, which prove to be broken. Someone has broken the lamps and the task of the small group is to find out what is the problem. The failures are related to different electric-circuit problems: for example there is no bulb in the circuit or the wiring polarity of the batteries have been reversed. (See Appendix 3: Problem-tasks for the last lesson)

### 6.6.1 Connection cards as a tool for uncovering thinking processes

For the design solution special connection cards were invented to uncover pupils thinking processes. The cards are enlarged and laminated pictures of real elements of the electric circuit consisting of batteries and bulbs (see the Figures 30 and 31). However, as wires we used real conductors with alligator clips, because they help in constructing the circuits. In addition, only some occasions the cards are used to replace the bulbs.



**Figure 30** *Connection cards used during the lessons.*



**Figure 31** *Third-graders drawing hypotheses of an electric circuit. The hypotheses have been made with the aid of connection cards.*

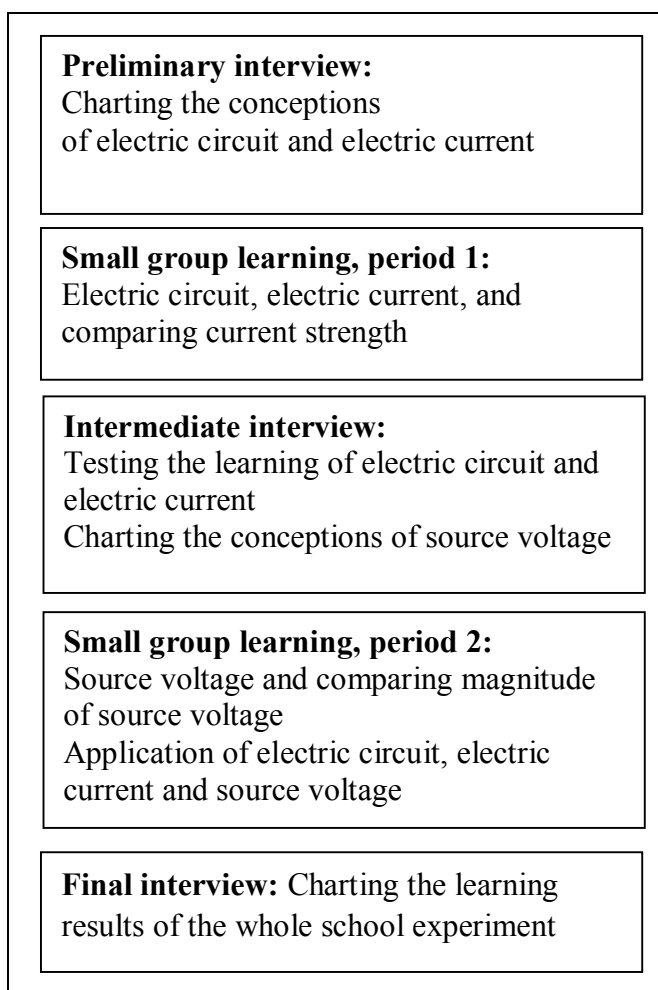
If thought from the perspective of model-based reasoning (section 3.3.1) the use of the cards can be seen as a modelling by simulation, a kind of thought experimenting. The use of cards is useful, because they enable different conceptions of the situation and make space for negotiation. The cards are used as a starting point for pupils' thinking, and with them the children can tell each other their own conceptions of the phenomenon.

Using connecting cards differs from the basic structure of studies researching pupils' external representations. While most of the studies concentrate on interviews with real connections (Borges and Gilbert 1999, 97) in this study interviews were used mainly with

the aid of connection cards and in connection to them. This is a new kind of situation, and really makes thinking more visible. Because none of the pupils can be sure of the right answer, their discussions are more democratic and more external representations are uncovered. In this study many hypotheses were made with the aid of connection cards. The connection cards were used in the preliminary, intermediate and final interviews. A typical way of using the cards was to ask the small group to construct a connection and discuss whether the circuit would work if the connection were real.

## **6.7 Structural outcome – teaching experiment**

This chapter describes the teaching experiment (structural outcome), the last part of the designing process of this study. At the background of the teaching experiment are above depicted teaching model of DC-circuit phenomena (subject matter outcome) (6.5) and talk-activating learning environment (pedagogical outcome) 6.6. The teaching experiment has particularly been constructed to support the empirical concept formation process, and taking into account historical models and the pupils' general external representations of the DC-circuit phenomena. The role of teacher is active and guiding, but the pupils in a small group are also encouraged to process the external representations via new observations, comparisons and negotiations. Thus the approach used is as described earlier in section 3.4.



**Figure 32** *The structural outcome of the design solution: teaching experiment. See also Table 6 for the timetable of the teaching experiment.*

Figure 32 includes the structure of the teaching experiment of DC-circuit phenomena. The teaching experiment consists of five parts; the experiment begins with a preliminary interview, goes on to a small group teaching experiment 1, is continued by an intermediate interview, goes on by the second teaching experiment, and finishes in a final interview.

### *Interviews*

Interviewing the pupils was divided into three phases: a preliminary interview, an intermediate interview and a final interview (see Figure 32 and Table 6). The first interview, the preliminary interview, which took place just before the lessons also included a preparatory section for the lessons. The small group of pupils was interviewed in the preliminary interview.

The subject matter goal of the *preliminary interview* was to chart pupils external representations of an electric circuit and electric current (see teaching model, section 6.5). In addition, from the standpoint of learning, the interview was of a preparatory nature



setting up a hypothesis for the electric circuit and the electric current for the first teaching experiment.

Connection cards were used as pedagogical solutions in the preliminary interview. Different connections were constructed with the connection cards, which the small group used when discussing the functioning of the electric circuit.

The goal of the *intermediate interview* was to test the learning of the first period and to chart teaching experiment two. The subject matter goals of the interview were testing the learning of the electric circuit and the electric current. Moreover, the conceptions of the source voltage were charted. The connection cards were also used in the intermediate interview. This time the teacher had made different connections and asked a pair of pupils at a time to explain different situations. Moreover, direct questions concerning the electric circuit and the electric current were asked.

The aim of the *final interview* was to chart the learning results of the whole teaching experiment. Pair-interviews were used in this phase, with writing tasks, and the connection cards. The goal of pair-interviews was to activate all pupils. While the pairs were being interviewed the rest of the group were answering the writing tasks.

### *Lessons*

To activate pupils' talk as much as possible the lessons were realised as small group discussions. The role of the teacher was to guide learning and negotiation on the grounds of the teaching model described in section 6.5, act as a chairman, and to encourage all to participate. The talk was activated by connection cards, claim cards, a word-explanation game, a true or false –explanation game, a dollhouse-electrification task, and by the broken pocket lamp problem-solving task .

The working method in a small group was as follows: firstly hypotheses were made with the connection cards; secondly observations were made with real connections; and thirdly the observations were discussed, teacher summarised the observations and emphasised the main subject matter. The hypotheses were arrived at in the small group by negotiation, and everyone had a chance to express his/her opinion. The phase of observation also included negotiation. The observations were also compared to the original hypotheses. So, the working method freely followed the ideas of the hypothetical-deductive learning cycle (4.3.2.2).

The last lesson differed from other lessons because of its concluding nature. The summing up was organised by applied tasks, which were designed on the grounds of the earlier lessons. During the last lesson the small group was divided into pairs that solved two problem-tasks: the dollhouse-electrification and the problem of a broken pocket lamp (see section 6.6 and Appendix 3: Problem-tasks for the last lesson ).

### *Pedagogical conclusion of the design solution*

According to needs assessment presented in section 6.1 the pedagogical solutions require some elements to be useful for learning. In this design solution we used games, plays and applied problem tasks to put into practice the requirement for contextuality and the children's world (B1). The connection cards and other charting ways were used to activate the children's thinking (A2) and make it possible to work with inexpensive equipment

(B2). The prolific concrete experimental tasks with hypotheses and negotiations activated practical work (A1), activated work and study, and gave experiences of the physical phenomena (B3). Moreover the pupil-centred small group working activated pupils in their practical work, thinking, and generally in their work and study (A1, A2, A3).

## 7 Results 2: Development of external representations of DC-circuit phenomena in a small group

The electricity goes off, and then the bulbs also go off. And when the electricity goes off, then also the fusing goes off.

*Matti*

As mentioned in section 1.2.1, one important starting point for this study has been the problem of “how to guide pupils to learn”. On the grounds of recent educational studies, small group learning has a positive effect on learning, so it has been chosen for the approach of learning in this phase of the study. This chapter will examine the learning process of DC-circuit phenomena in the small group (research question 2) during the teaching experiment. The learning process will be reviewed from the viewpoint of modelling, thus the small group’s external representations of the subject matter are on the focus: *How will the small group’s external representations of DC-circuit phenomena develop during the teaching experiment?* The placement of this phase to the whole structure of the study is shown in Figure 1.

### *Cognitive processes of a small group include modelling*

In analysing the modelling process of a small group, its learning has been studied from the standpoint of cognitive processes attained, and from the standpoint of knowledge constructing. The purpose of scrutinising *cognitive processes* is to determine if there exist higher-order thinking skills including modelling processes in the talk of a small group. As discussed in sections 2.2.2 and 3.3, one form of cognitive processes is modelling, which requires higher-order thinking skills: the sub-category explaining involves constructing the first cause-and-effect models, and the process of creating new knowledge also involves modelling, i.e., putting elements together to form a coherent or a functional whole. Thus, in the first phase of analysing the research question 2, the aim is to chart the small group’s cognitive processes by content analysis in order to find possible modelling processes. So sub question 2.1 is: *What kind of talk exists in the small group’s learning?* (See section 7.2.)

### *From the small group’s original external representations to more developed models of DC-circuit phenomena*

The second phase of the analysis in this chapter will focus on the *knowledge construction* itself: the aim is to follow the paths of the small group in developing its external representations of DC-circuit phenomena in the direction of more scientific ones. Thus, the study will in fact go on from the results of the sub question 2.1, because at the highest levels of cognitive processes analysed in sub question 2.1 are supposed to exist in the small group’s external representations. Thus, providing an answer for sub questions 2.2 actually means focusing on the results of 2.1.

As discussed in section 3.4, the learning process is considered from the view of the learner (or the small group). According to this view, the small group’s original external

representations are the starting point of the knowledge construction. The aim of teaching and learning is to guide the original external representations towards more developed (scientific) models. In this phase of the analysis, the learning of the small group is followed step by step during sequential learning sessions. In the analysis, every session is considered an episode, within the small group as it negotiates its external representation of a certain DC-circuit phenomenon. The analysis follows these paths of developing external representations of the small group and answers to sub question 2.2: *What kinds of external representations for DC-circuit phenomena exist in the small group discourse during the teaching experiment?* (See section 7.3.)

The tool for analysis used is the frame of model (external representation), designed for this study (see section 3.5, and especially Figure 8), and has already been applied in analysing the historical data (see chapter 5). According to the framework of the model, the fragments of external representations of DC-circuit phenomena consist of observation and perception, understanding causal relations, forming gestalts, doing prequantitative experiments, and finding concepts and empirical laws common to them. This modelling can also include the first theoretical explanations of DC-circuit phenomena.

## 7.1 Data selection

To analyse the external representations of the small groups participated to the teaching experiment the videos of the two groups – one of third-graders and one of fifth-graders – were watched tentatively. Basically, both teaching experiments succeeded, but because of the large amount of the data, there had to be a solution to choose only one of the groups to analysis. Selecting the small group of third-graders was based on its better activity in discussions and the abandonment of one group member in the small group of fifth-graders. The teaching experiment for the third-graders succeeded especially well, and this was manifested in lively and active discussions and a keenness to learn. Thus, there were in fact no difficulties in finding suitable episodes to analyse.

For analysing the small group's modelling processes from the standpoint of cognitive processes (sub questions 2.1) the following critical episodes were chosen: episode 1) constructing an electric circuit of one battery and several bulbs with connection cards (PI), episode 2) constructing an electric circuit of one battery and several bulbs with real connections (2<sup>nd</sup> L). These are the episodes used to analyse the talk of a small group.

For sub question 2.2 the following episodes from the interviews were chosen: (preliminary interview (PI), intermediate interview (II), and final interview (FI)). Also all the lessons (1<sup>st</sup> L, 2<sup>nd</sup> L, 3<sup>rd</sup> L, 4<sup>th</sup> L and 5<sup>th</sup> L) belonged to the analysis. However, in these analyses we concentrated on the most fruitful parts of the discourses.

## 7.2 Categories of cognitive process dimensions

In this phase of analysis, the stress was on the learning process of the small group during two consecutive learning situations (PI and 2<sup>nd</sup> L). The aim was to study whether the talk included clues to the developing external representations of the group. Furthermore, the special interest of the analysis was also to compare how the two different environments – using connection cards and real connections – affected the level of the talk in the same small group. So the analysis also acted as a test of the pedagogical innovation of connection cards (6.6.1) to activate and uncover the small group’s thinking. For this reason the study used hierarchical categories of cognitive process in ordering the categories of talk in the group. The results of this chapter have also been discussed in Kallunki (2008).

The episodes chosen for the analysis were two learning situations, in which the same small group had just finished constructing a connection of one battery and several bulbs in series. The first episode occurs during the preliminary interview of the small group, and in this situation the special connection cards are used. The second episode takes place later, during the second lesson as part of the learning concepts for the electric circuit and the electric current. In this phase, similar connections are made with real components. In both episodes, the question asked was the following: *“Is it possible to light two or more bulbs with a single battery (in series)?”* The analysis focused on the process of the small group’s talk during each episode and comparisons between the episodes were also made.


The data was analysed by qualitative content analysis (see 4.4.1) using an inductive approach, which means that the stress of the analysis was on the data. The analysis started with transcription of the data. After that the data was read several times, and during this process different categories of pupil’s talk emerged. Then the data based categories of pupil’s talk were compared into the hierarchical categories of cognitive process, which were used to support the order of categories. Because both situations were well delimited to the actual negotiation of the question, the pupils’ talk was also confined to this type of discussion. Thus, it was not surprising that the categories found did not encompass all categories of the cognitive process dimension – the categories remember, understand, apply, analyse, evaluate, and create were present– (cf. Table 2), but the category evaluate was missing.

After the first analysis, eleven categories describing the level of pupils’ talk in different lines were found. In classifying the forms of pupil’s talk three differentiating factors were developed. In order of importance these factors were: give reasons, pupil’s own consideration, and initiative. The aim of these factors was to differentiate levels of pupils’ talk. The original categories, and reducing the number of categories are described in Table 10.

The forms of pupil’s talk found were also compared with the categories of the cognitive process dimension to look for support for the order of categories, and on this grounds the categories were arranged in an ordinal scale. The biggest changes in categories in proportion to the original categories were: 1) Renaming a category of “developing others’ ideas” to “creative talk” and rising it to the highest level. This change was grounded on the categories of cognitive process, where the highest level of pupils’

thinking skills – create – fits to this category. 2) Uniting the categories of “question or propose dealing with the content” and “think-aloud” to a category of “think-aloud”, the category that expresses the pupils’ own considerations, but the thoughts were incomplete. This category fits the categories of analyse and understand in cognitive processes. 3) Uniting the categories of “clear opinion” and “agree/disagree” to a common category, which describes understanding without reasoning. 4) Raising the category of “technical talk” above “answering”, because of the backing of the category “apply” in cognitive processes. Although the talk in this category mainly related to experimenting, it however signified an initiative and included an element of applying knowledge, whereas the category “answering” purely expressed remembering. To increase the credibility of the analysis, the described phases of analysis were checked and discussed several times by three co-researchers.

**Table 10** *Categories of pupils' talk at different phases of content analysis: E = explanatory talk, DI = developing others' ideas, QP = question or propose dealing with the content, TA = think-aloud, CO = clear opinion, AG = agree, DAG = disagree, A = answering, TT = technical talk concerning the experiment, NK = I don't know answer, OT = pupil's other talk and C = creative talk.*

	1 <sup>st</sup> analysis	2 <sup>nd</sup> analysis	3 <sup>rd</sup> analysis
 <b>Level of talk rises</b>	E	E	C
	DI	DI	E
	QP	QP	TA
	TA	TA	
	CO	CO	CO
	AG	AG/DAG	
	DAG		
	A	A	TT
	TT	TT	A
	NK	NK	
	OT	OT	OT

### 7.2.1 Results: Cognitive processes of DC-circuit phenomena during small group learning

The found categories of pupil's talk are from the lowest level of talk to the highest level: 1) other talk, 2) answering, 3) technical talk, 4) clear opinion 5) thinking aloud 6) explanatory talk, and 7) creative talk. As described in Table 11 below, the categories of talk from the 4<sup>th</sup> category onwards include explanatory or understanding demanding aspects of talk at least. Thus they are categorised as a higher level of talk.

**Table 11** *Classified categories of pupil's talk. In ordering categories, similarities with categories of cognitive processes, as well as pupil's reasoning, consideration, and initiative have been used.*

Category of pupil's talk	Categories of cognitive processes (Anderson and Krathwohl 2001, Table 2)	Notes	Examples of pupil's talk
7. Creative talk C Creating a reasoned new model Developing an explanation for some one else	Create	Explanatory talk is understood as a first level phase of the modelling process. Explaining means constructing a cause-and-effect model of a system, whereas in creative talk elements of earlier model the reorganised into a new pattern or structure [8]	Well, from here comes this kind of (circle). It goes like this. (a new explanation of the same phenomenon)
6. Explanatory talk E Expressing a reasoned explanation Micro- or macro level explanation A complete thought	Explain		When minus goes here, then plus goes here. (micro level explanation)  If every bulb had its own battery it would work. (macro level explanation)
5. Thinking aloud TA Considering aloud The thought or explanation is incomplete A clear answer to the teacher's complementary question in the context of TA Expressing a question or a proposition of the phenomenon More than an opinion	Analyse Understand	This category is classified as an intermediate category, because it clearly includes higher level thinking, but the thoughts are not completely expressed.	If it leaves from here (points his fingers to the different directions from the battery ...or ,then again it won't.
4. Clear opinion CO Expressing one's own opinion clearly, but without reasoning in the context of explanation of the phenomenon Agree/disagree Initiative	Understand	In this category, the talk of pupils' is confident, but because of lack of reasoning or wider considerations it is situated below the earlier categories.	It does not work!
3. Technical talk TT Initiative talk related to experimenting (constructing a connection etc.) Not including TA	Apply Remember	The category includes talk related to the real experimenting, and is situated above answering, because it includes the element of initiative.	So, and then you can connect it (wire) here, to this bulb.
2. Answering A Answering the teacher's question Not including reasoning Not initiative answer Also "I don't know" – answer	Remember (recognize or recall)	This category is plausibly based on remembering, because the answers do not include reasoning.	I don't know.
1. Other talk OT Talk not relating to the subject			Our light is cool! But our light is even cooler.

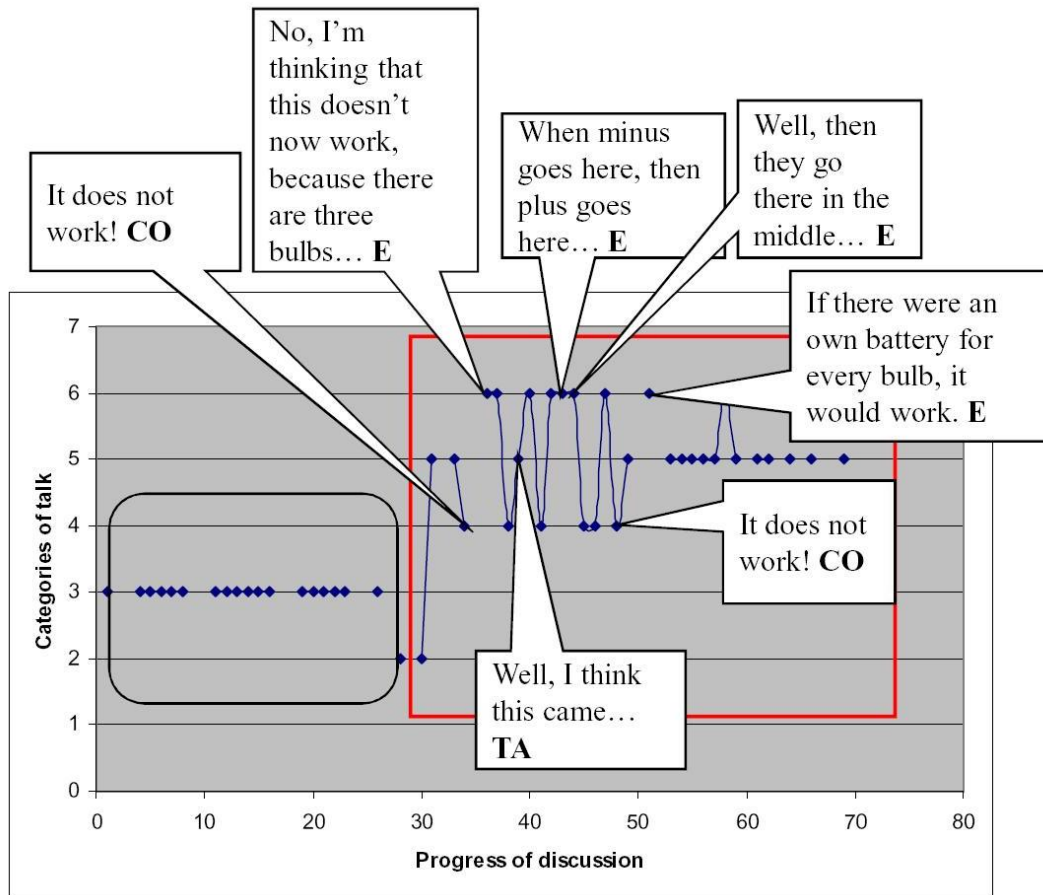


## 7.2.2 Results: Level of cognitive processes with connection cards and real connections

Finally the data was classified into the categories. The classification was done twice at intervals of several weeks, the classification was discussed several times with other co-researchers, and the results were also introduced at an international conference (Kallunki 2008). Figure 33 and Figure 34 portray the analysis of two learning episodes of the same small group. The figures show the levels of cognitive processes with graphic representations, in which the progress of the discussion appears from horizontal axis. The numerical values in the axis describe the number of lines in the discussions, and therefore the axis also depicts time. The vertical axis therefore, illustrates the categories of talk in the small group with ordinal scale. In this axis the numerical value 1 refers to the lowest level of pupil talk classified in Table 11. Respectively, the value 6 equates the highest category (creative talk) of talk.

In Figure 33 and Figure 34 both episodes include a phase of constructing (marked by a rounded rectangle), and a phase of explaining (marked by a rectangle). In both episodes, the question asked is the following: *“Is it possible to light two or more bulbs with a single battery?”* In the phase of constructing connections the level of talk remains at that of technical talk i.e., a typical discussion in the context of real experimenting: *“So, and then you can connect it (wire) here, to this bulb”* (TT).

The phase of explaining is quite different; the level of talk rises in both episodes. However, the talk with the connection cards has a higher-level average than the talk with real connections. In the case of the connection cards, the explaining period is longer and it is more negotiating by nature than discussing with real connections. Dialogue like *“No, I’m not thinking that this doesn’t now work, because there are three bulbs...”* (E), is a typical example of explanatory talk, which gives a macro level explanation of the situation. In proportion, in the utterance *“When minus goes here, then plus goes here...”* (E), the explanation is given at the micro level and it describes the phenomenon theoretically. So, the small group seems to concentrate more on thinking with connection cards and its external representation of electric-current phenomenon clearly appears. The group concludes a common external representation of two electric currents. See Appendix 4: Connecting several bulbs in series with connection cards – Constructing electric circuits of three or five bulbs for more analysis of the small group’s talk with connection cards.

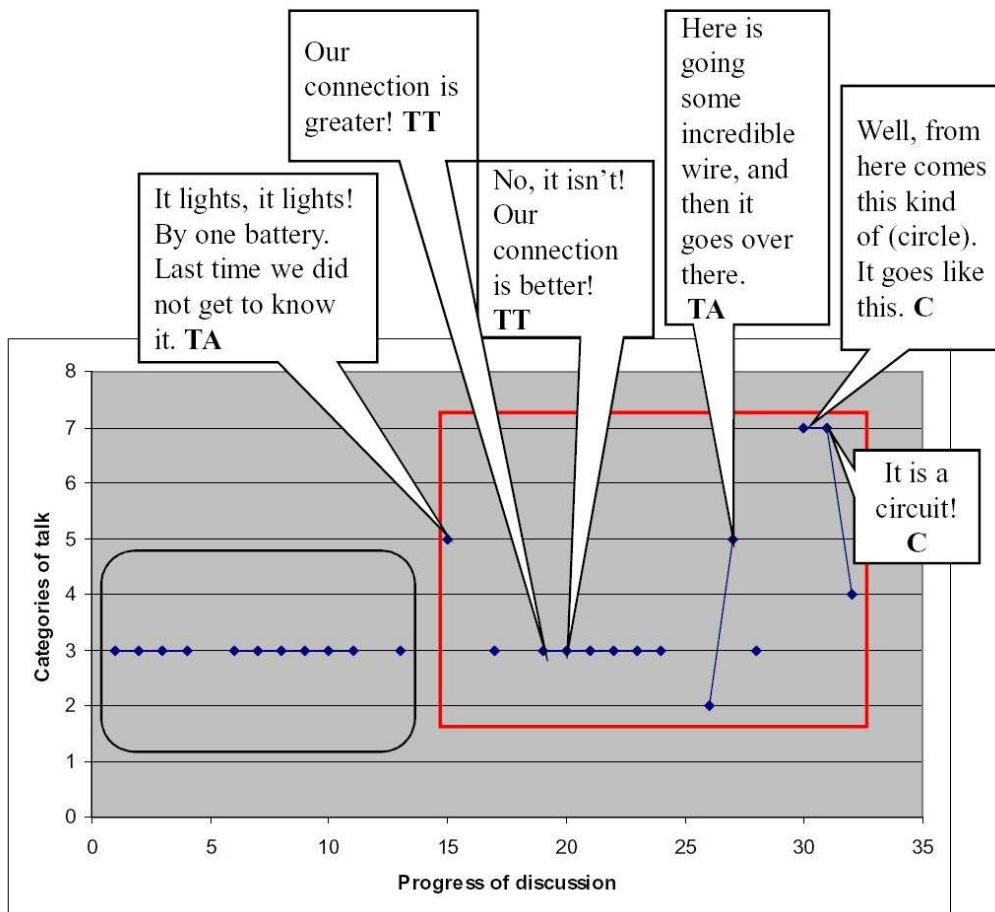


**Figure 33** *Analysed small group's talk with connection cards during the Preliminary Interview (PI). The progress of the discussion appears in the horizontal axis. The numerical values in the axis describe the number of lines in the discussions, and therefore the axis also depicts time. The vertical axis illustrates the categories of talk in the small group with an ordinal scale. The part of discussion inside the rectangle is the actual explaining episode. Before that the small group had constructed a connection of one battery and several bulbs in series.*

Talk with real connections takes place during the second lesson of the teaching experiment. Between the two episodes, the small group had made simple connections with real components, but used only one bulb. The group had also learnt the concept of the electric circuit. As it appears from Figure 34 the small group has a real problem in concentrating on thinking with real bulbs. A greater part of group's attention centres on admiring and comparing the lights of the bulbs instead of the conflict between their earlier representations that this kind of connection would not work: "Our bulbs lit, yours did not. Our bulbs lit, yours didn't!" (TT).

There exists, however, a single clue of a possible challenging of the earlier representation in the first lines: "It lights, with one battery. The last time we did not get to know it" (TA). At last, at the end of the episode the small group creates a new explanation; the erroneous representation of two electric currents is replaced by the correct model, the electric circuit: "Well, from here comes this kind of (circle). It goes like this"

(C), and “It is a circuit!” (C). There is also a continuum in the learning process between the episodes: while the group has achieved the level of explanatory talk (the representation of two electric currents) during the first episode, it progresses to the level of creative talk in the second episode (the representation of the electric circuit). Thus, the last lines below describe the highest level of talk, creative talk, when a new model is created to better explain the phenomenon. See longer period of the discussion with real connections in Appendix 5: Analysis leading to the fragment “bulbs in series light because of the electric circuit”.



**Figure 34** *The small group’s talk with real connections during the 2<sup>nd</sup> Lesson (2<sup>nd</sup> L). The progress of the discussion appears in the horizontal axis. The numerical values in the axis describe the number of lines in the discussions, and therefore the axis also depicts time. The vertical axis illustrates the categories of talk in the small group with an ordinal scale. The found categories of pupil’s talk are: 1) other talk, 2) answering, 3) technical talk, 4) clear opinion 5) thinking aloud 6) explanatory talk, and 7) creative talk.*

### 7.2.3 Conclusions of sub-question 2.1

The analysis reveals that the small group used talk of different levels in different situations. The lowest level of talk appeared while doing concrete experiments, whereas while discussing with ready connections the level of their talk rose. According to the analysis the talk of the small group included seven different types of talk of which the two highest – creative talk and explanatory talk – clearly included modelling or external representations of pupils. Also, the third level of talk, thinking aloud, could be regarded at least partially, to contain ideas of the external representations.

The results encourage the use of connection cards to make children's thinking more visible and to uncover their external representations of DC-circuit phenomena. The use of the connection cards raises the level of the children's talk, lengthens the explanatory period, and helps children to concentrate better on thinking. In the episode analysed, the talk with connection cards is mainly higher-order thinking, expressing a deep motivation to the task. The use of the connection cards fits with the use of the real components; the connection cards function as a starting point to learning and the pupils seem to regard them as a natural part of learning when they unite the situations of connecting with the cards and the real components.

By using the connection cards, it becomes easier to plan instruction to promote learning. The use of cards appears to be a democratic tool in activating talk; because none of them knows the right answer, all the members of the small group get an opportunity to participate in the negotiation.

## 7.3 Fragments of external representations of DC-circuit phenomena

The results of sub question 2.1 proved that there really exist higher-order cognitive processes, or modelling processes in the discussions of the small group. In sub question 2.2 the whole modelling process was traced by searching for the appearance of fragments for external representations of DC-circuit phenomena during the teaching experiment: *What kinds of external representations for DC-circuit phenomena exist in the small group discourse during the teaching experiment?*

The analysis was done using an abductive content analysis respecting both theory and empirical data (see section 4.4.1). This means that the consensus model of DC-circuit phenomena (see section 6.4), as well as results of historical models of DC-circuit phenomena described in Chapter 5 affected the analysis of the empirical data acting as a starting point to search for categories. However, the empirical data itself was the most important; the fragment maps of DC-circuit phenomena described in this chapter are based on empirical data. The frame of external representations designed in section 3.5 was used as a tool of analysis.

The data was analysed by content analysis (see section 4.4.1) in the following way: 1) The data was lettered. 2) The data was read several times and classification was done by arranging it into classes of different conceptions of the subject matter. 3) In the next phase

similar types of conceptions were collected together. 4) The next step of analysis was to name the classes and to reduce its content. The analysis was started from a whole critical episode (an interview or a lesson, see section 7.1). However, it soon concentrated on the most fruitful parts of the discourses meaning particularly the phases of higher-order thinking of talk. The aim of the analysis was to search for conceptions, which were accepted by the whole small group, thus the results can be interpreted to stand for the small group's common external representations during the teaching experiment.

The analysis uncovered that the small group's learning process appeared in the form of little fragments, which represent parts of the final external representation. At the beginning of every analysis the emerged fragments were classified into categories to show the starting point of learning. Afterwards these fragments develop and interconnect showing the process of learning.

The sequential fragments of the small group's external representations (cf. Vosniadou 2007, 19) are shown by graphic representations (see Figure 35, Figure 37 and Figure 38), in which the progress of the teaching experiment appears from an ordinal scale in the horizontal axis. The vertical axis shows the original fragments arranged into categories. The vertical axis has a nominal scale, in which the order of categories is set to make it possible to visualise best the process of learning i.e. the interconnecting of fragments.

In a graphic representation, every fragment of the external representation of the DC-circuit phenomenon stands for part of the whole picture of the small group's developing external representation. Thus, the graphs presented have been arranged in a way to best show the process of external representations. On the other hand, from the stand point of a single fragment, increases in the level of the fragments generally means learning. The only exceptions to this are the final external representations, which also include some undeveloped theoretical explanations and do not represent learning in this respect.

The fragment maps of DC-circuit phenomena are read from left to right. The different shades in a map represent the separate paths of fragments of external representations, and the final external representation is placed in a rectangle marked by dashed lines. Moreover, in the fragment maps one category of external representation of DC-circuit phenomenon is printed in bold type, which means that the interconnecting of fragments during the teaching experiment takes place towards this category.

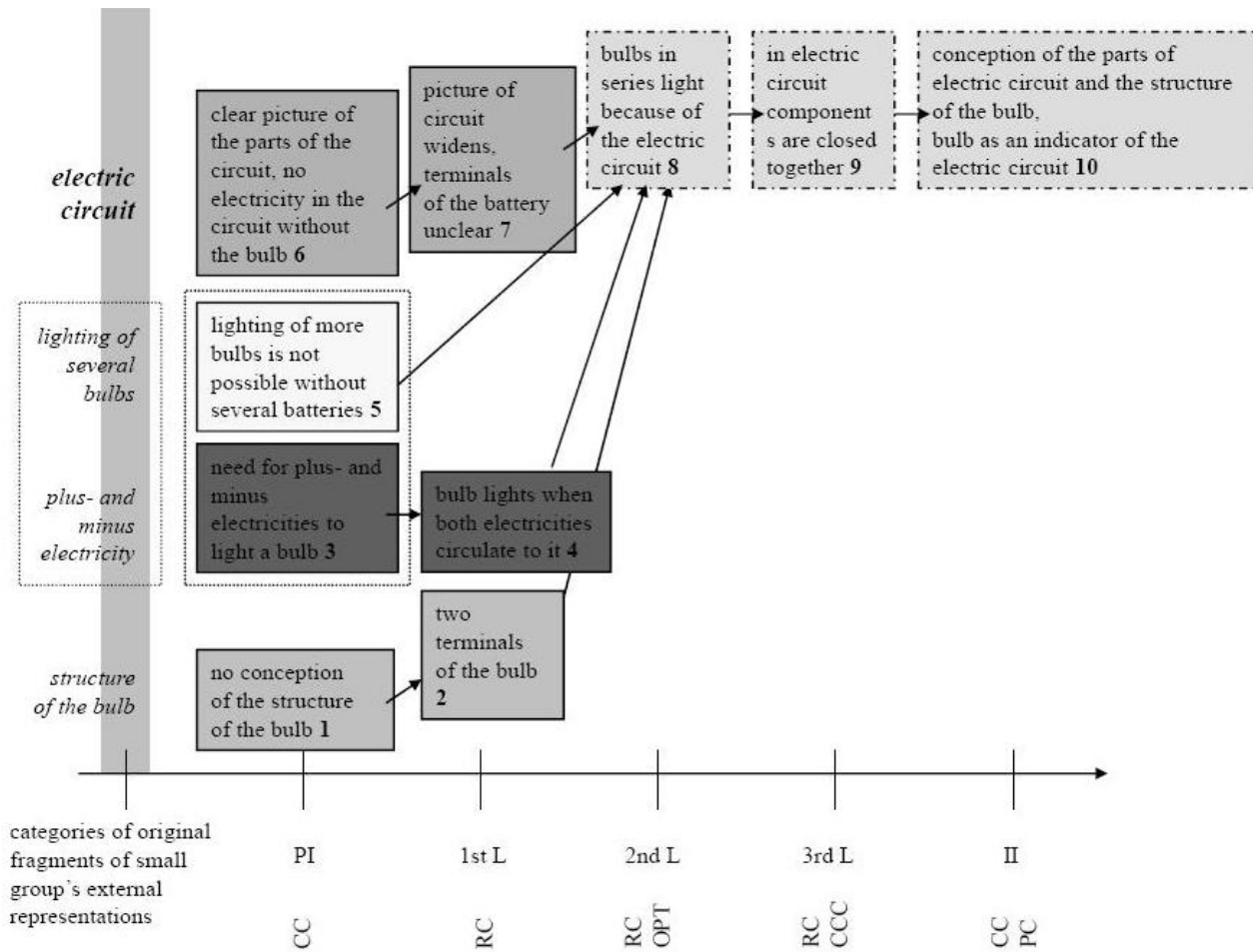
The types of experiments, which are applied during the interviews and lessons are also depicted below the horizontal axis in fragment maps. The abbreviation CC indicates experiments by connection cards, RC for experiments by real connections, CCC for claim card competitions, PC for picture cards, OPT for open problem tasks, WEG for word explanation games, and P for pictures.

### **7.3.1 Results: Small group's external representations of the electric circuit**

As it was discussed in section 6.7 the first half of the teaching experiment focused on experiments on electric circuit and electric current. During these experiments and discussions, the small group identified different parts of the electric circuit, lit a bulb with a single battery, puzzled over different ways of connecting a bulb and a battery, pondered

on the lighting order of several bulbs, connected more bulbs in series, and connected a switch to the electric circuit. The types of experiments used were CC, RC, CCC, and PC, see the horizontal axis of following figures (Figure 35, Figure 37 and Figure 38).

Figure 35 portrays the fragment map of the external representation of the electric circuit. The period analysed is from preliminary interview (PI) to intermediate interview (II) also including lessons 1, 2 and 3 (1<sup>st</sup> L, 2<sup>nd</sup> L and 3<sup>rd</sup> L).



**Figure 35** The fragment map of external representation of the electric circuit. The conceptions in the rectangles are the fragments of external representations of the electric circuit.

Fragments of external representations concerning the electric circuit emerged in the content analysis. These fragments were arranged into four categories (see Figure 35 above). The category *structure of the bulb* describes the small group's external representation of the bulb as part of the electric circuit, but this category can also be understood generally to measure the understanding of any extra component as part of the electric circuit. The categories *plus- and minus electricity* and *lighting of several bulbs* are tied to each other; the former explains the functioning of the electric circuit by the nature of the electric current, whereas the latter tries to solve the concrete problem situation of lighting several bulbs with a single battery. The category *electric circuit* includes pupils' conceptions of the circuit as a whole.

*The fragment path (1 → 2): Structure of the bulb*

The small group's external representation of the electric circuit develops from the original fragments to the final representation through four fragment paths. The first path of the fragments (1 → 2) concerns a bulb as a part of the circuit. During the preliminary interview the *structure of the bulb* is a null fragment, which means that the small group has no conception of the structure of the bulb. This appears from the small group's several different connections of bulb to the circuit by the connections of the connection cards. Although the structure of the bulb is just a little detail, it has a wider meaning in understanding different components as "a piece of conducting wire" and thus part of the circuit. After experiments with real connections (1<sup>st</sup>L) the small group identifies the terminals of the bulb. The fragment perceives the small group's external representation of the electric circuit on a concrete level being based on observations and the teacher's explanation. Table 12 includes lines of the original talk and their reduced expressions. The last column is the final fragment (2), which is in this way reduced from the talk of the small group.



**Table 12** *Analysis leading to the fragment, Two terminals of the bulb.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
T: What points of the bulb do you touch with them? M: I' m touching this line. N: And me to this black here below. ... L: The other to the line and the other above.	There are two points in the bulb, which have to be touched to light it.	<b>Two terminals of the bulb (2)</b>
T: Would it light, if we put both (conducting wires) there to the bottom? M: Yes, it would! L: No. M: Surely. No, it wouldn' t, because we tried it just a moment ago.	Uncertainty of the two points to be touched.	
L: Through such a route. When you put one wire from here, so it goes over there. And when you put one wire from here, it goes from here to there.	Little wires inside the bulb, a route.	

*Plus- and minus electricity (3 → 4) and Lighting of several bulbs (5)*

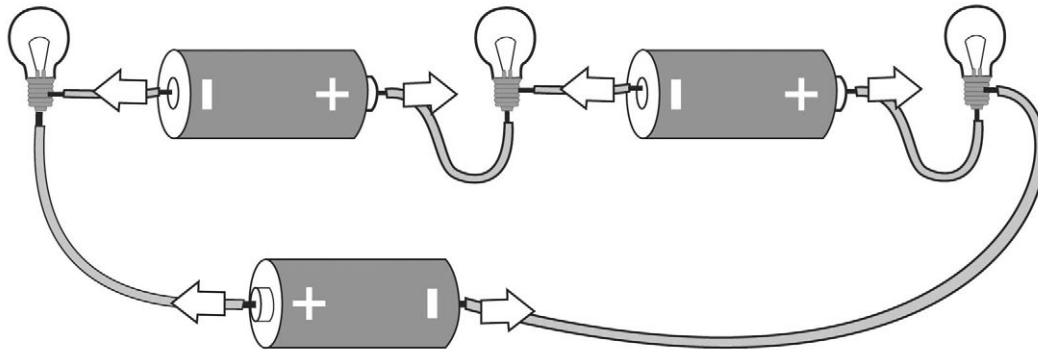
During the PI the small group had problems in explaining the situation in which the circuit was formed of one battery and several bulbs (5). The teacher asked if it was possible to light the bulbs with the battery. The small group connected the circuit with connection cards, but concluded with strong conviction that the bulbs would not light with a single battery. On the background of this perception was the small group's theoretical explanation of plus- and minus electricities, according to which a bulb lights only when both plus and minus electricities are present. The table below shows the analysis of this episode. See Appendix 6: Lighting the bulb, connections with connection cards for longer period of the talk of the small group in this context.

**Table 13** *Analysis leading to fragments 3 and 5.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
L: It would not light, because the other is only plus and then it needs this plus and minus, so it will light.	Need for plus- and minus electricities to light a bulb	<p><b>Need for plus- and minus electricities to light a bulb (3)</b></p> <p><b>Lighting of more bulbs is not possible without several batteries (5)</b></p>
M: Minus comes from here and plus comes from here.	Plus and minus from the battery	
L: I' m not sure. I think that it would work, so that both would light. But however I think that, because here go these two wires and here is this crosswise (middle), so the light does not go on. Because only plus goes here and only minus goes here.	From the battery goes plus and minus currents to opposite directions. These currents stop to the first bulb.	
L: ...this cannot be both (plus and minus currents)	There cannot be both plus and minus currents between the two bulbs in series.	
N: No, I' m thinking that this doesn' t now work, because there are three bulbs...	The three bulbs cannot be lit by a single battery, there is a need for more batteries.	
M: It cannot work, because there should be two batteries.		
L: Three batteries. M: When the minus goes here, and then the plus over here. L: Well, then they go there in the middle. M: So... but... La: ...it does not work! M: No. We would need more batteries. L: Yes. N: Three. L: If every bulb would have its own battery, it would work.	Bulbs will light, if every bulb has its own battery.	

The small group did not develop in relation to the fragment path (3→4) during the PI and the 1<sup>st</sup> lesson, thus both fragments of this external representation are placed at the same level. Although the fragments *Need for plus- and minus electricities to light a bulb (3)* and *Lighting of more bulbs is not possible without several batteries (5)* are very close, they are classified in different categories. This has been done because they stand for different aspects in the frame of the model; the former offers a theoretical explanation to a situation described in the latter. Figure 36 below is a diagram uniting fragments 3 and 5 of

the small group. As it appears from the figure the small group thought in this phase that from every battery two electric currents flow in opposite directions. When the two different currents meet in a bulb, it lights.



**Figure 36** *A bulb lights when two different electric currents make it.*

#### *Electric circuit*

The fragment path *Electric circuit* (6→7) includes fragments of circuit as a whole. During the PI the small group seems to have quite a clear picture of the parts of the circuit; the small group quickly lists the components needed to light the bulb (a battery, a wire, electricity and bulbs). Furthermore the pupils meticulously mention that the wire has to be fixed by a paper clip. In this phase the picture also includes an erroneous conception that there does not exist electricity in the circuit without the bulb (see Table 14). During the next session (1<sup>st</sup> L) the picture of the circuit widens in discussions of different circuits of electrical apparatuses at home. This time however the terminals of the battery seem to be a little bit unclear for some members of the group. Generally speaking, the fragment path (6→7) very clearly represents the pupils' observations of working electric circuits.

**Table 14** *Analysis leading to the fragment, A clear picture of the parts of the circuit, no electricity in the circuit without the bulb (6).*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
M: Battery. L: Electric wire... or a wire, which goes to the battery. M: During the technical work we fixed (the wire) to the battery with a clip. L: Electricity... and functioning electric lamps.	Parts of the circuit: battery, electric wire to the battery, clips, electricity, functioning electric lamps	<b>A clear picture of the parts of the circuit, no electricity in the circuit without the bulb (6)</b>
L: These (wires) are needed two. N: Yes.	Two wires	
L: That one to the minus side and the other to the plus one. And then the other, two strings needed.	Wires are connected to the minus and plus poles of the battery	
T: If we take this bulb away and connect these wires? L: No electricity.	No electricity without bulb in the circuit.	
T: What happens if we take away this battery and connect these (wires)? M: No, no. L: No. N: No. L: There is no electricity.	Removing battery from the electric circuit removes the electricity	

The second lesson (2<sup>nd</sup> L) produces a turning point in the modelling process of the small group. The small group is given the task to build the same connection, which had done during the PI with the connection cards. This time the connection is switched by real connections. The biggest insight takes place when the small group explains why all the bulbs in series light by contrast the earlier conceptions (compare it to fragment 5). The small group has two reason to search for a new explanation to the phenomenon: firstly the observations are strongly against their earlier conception (fragment 5) and secondly because of the teacher's guiding. Namely, in the beginning of the second lesson the teacher briefly refuted the conception of plus- and minus electricity. The teacher did not give any new explanation, but only refuted the wrong conception. (see Appendix 7: The teacher's guiding role )

According to fragment 8 *the bulbs in series light because of the electric circuit* (see Table 15), thus the small group clearly develops parts in relation to earlier fragments of external representation of the earlier circuit. Fragment 8 includes a clear picture of the electric circuit (fragments 6→7), a new explanation to the problematic fragments concerning plus- and minus electricity and lighting of several bulbs (3→4→5), and an

extended conception of the bulb as a lengthening of the electric circuit (1→2). See also Appendix 5: Analysis leading to the fragment "bulbs in series light because of the electric circuit"

**Table 15** *Analysis leading to the fragment, Bulbs in series light because of the electric circuit.*

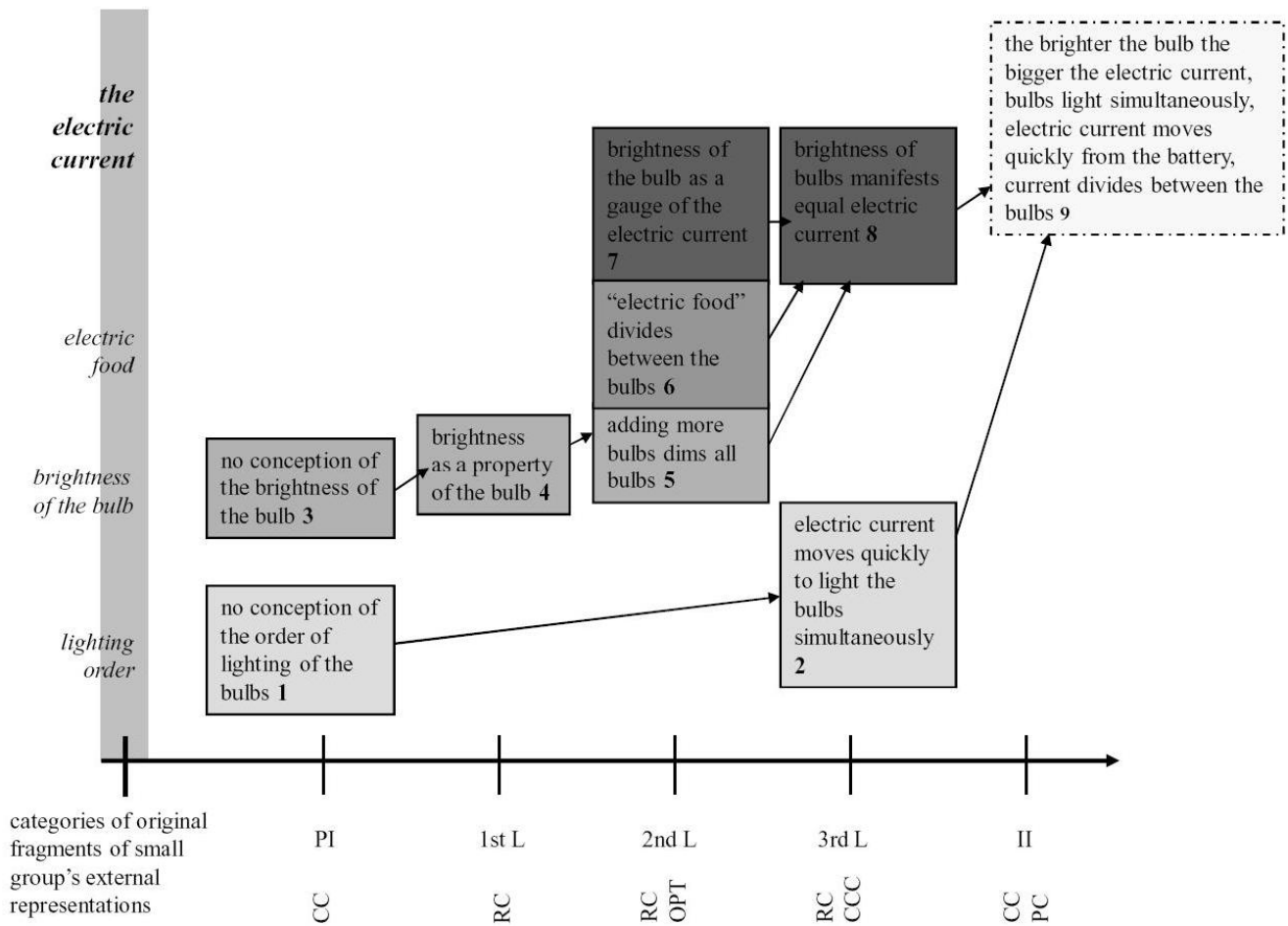
ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
<p>T: Is it possible to light these two bulbs with this single battery?            L: I know. No, I don' t know. Yes, no. Yes, no.            N: Yes? Yes!            L: No it isn' t, because here we have only two wires to one battery...            M: Yes, but...            L: ...and then there are four places.            N: If we took one extra wire?</p>	<p>Bulbs can be lit with one battery, but extra wires are needed</p>	<p><b>Bulbs in series light because of the electric circuit (8)</b></p>
<p>L: It lights, it lights! with one battery. Yes, last time we did not get to know it.</p>	<p>Bulbs light surprisingly</p>	
<p>T: What do you think about that?            L: I don' t know.            M: Here is going some incredible wire, and then it goes over there. Those are taking it electricity, and then it comes from this bulb...            Mi: Well, from here comes this kind of (circle). It goes like this.            M: It is a circuit!</p>	<p>Bulbs light, because they are in a circuit.</p>	

The role of fragments 9 and 10 (3<sup>rd</sup> L and II) is to throw more light on fragment 8 and to conclude small group's external representation of the electric circuit. The electric circuit is understood as a system in which all the components are closed together (9), moreover in the intermediate interview (II) the small group repeats its conception of the parts of the electric circuit and the structure of the bulb. A new point which appears in II is to understand the bulb as an indicator of the electric circuit (10).

### 7.3.2 Results: Small group's external representations of the electric current

Figure 37 portrays the fragment map of the external representation of the electric current. The period analysed is from preliminary interview (PI) to intermediate interview (II) also including the lessons 1, 2 and 3 (1<sup>st</sup> L, 2<sup>nd</sup> L and 3<sup>rd</sup> L).

Fragments of external representations concerning the electric current emerged in the content analysis. These fragments were arranged into four categories (see Figure 37 below): 1) *lighting order*, 2) *brightness of the bulb*, 3) *electric food*, and 4) *the electric current*. The first category of the small group's external representation deals with the nature of the electric current particularly with the question of the bulbs' lighting order. The second and fourth categories represent the small group's different levels of external representations of causal relations and prequantification. The third category stands for a kind of theoretical explanation of the electric current, as well as the first category.



**Figure 37** *The fragment map for the external representation of the electric current developed by the small group.*

*Fragment path (1 → 2): Lighting order*

The first fragment path of external representation of the electric current belonged to the category of the *lighting order* of the bulbs. In this fragment path the nature of the electric current is in focus, thus the fragments give the first theoretical explanations of the electric-current phenomenon, which is quite a strong development. While the first fragment pictures a conception of a total unawareness of the order of lighting of the bulbs (1), the second fragment includes much more; the lighting of bulbs takes place simultaneously. However, the theoretical explanation uncovers an erroneous conception of the nature of the electric current. This appears from fragment 2 during the 3<sup>rd</sup> lesson: *The electric current moves quickly to light the bulbs simultaneously (2)*. As it becomes evident from Table 16, the fragment is based on real observations. The small group has just observed the simultaneous lighting of the bulbs in series and try to explain it. At the background of the theoretical explanation, there exists a conception of the battery as a source of electric current (see fragments 1 and 2, Figure 38), thus this new observation evokes a contradiction between the source and simultaneity. Thus it can be concluded that the fragment (2) represents a new attempt to solve the conflict between the theoretical explanation and empirical observation.

**Table 16**      *Content analysis leading to the fragment 2, Electric current moves quickly to light the bulbs simultaneously.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
<p>T: Now we will observe if all the bulbs light simultaneously.                      L: Here lights, lights, lights.                      M: All at once.                      N: Together.                      L: Together.                      M: This one lit at different times.                      T: Observe closely.                      M: I can' t, because Milja' s finger is in the way. Together.</p>	<p><b>Bulbs light simultaneously.</b></p>	<p><b>Electric current moves quickly to light the bulbs simultaneously (2)</b></p>
<p>T: Why do the bulbs light simultaneously? What does it mean?                      M: It means that...because electricity is so fast and its quantity is the same...                      L: It goes so quickly that it arrives in time everywhere.</p>	<p><b>Bulbs light simultaneously, because electricity arrives in time everywhere.</b></p>	



*Brightness of the bulb*

The second fragment path (3→4→5) builds an observation and perception –based gestalt of causal relations and the first prequantification of the concept of the electric current. During the preliminary interview the small group clearly had no idea of the different brightness of the bulbs (3). However, the situations changed in the first lesson, when the small group had several changes to construct different connections with real devices. There for the first time we heard expressions like “it appeared a smaller light from this bulb than from that earlier” and “you have a brighter light than we have” in the discussions. From these kinds of expressions it was concluded that the small group observed and perceived its external representation of the brightness of the bulb, and at this phase the brightness of a bulb seemed to be a particular property of a given bulb (4). The external representation clearly developed during the second lesson, when the small group expressed its first prequantitative fragment (5): *adding more bulbs dims all the bulbs*. The fragment represented the small group’s hypothesis before comparing experiments with different numbers of bulbs in the circuits. However, the small group had obviously made observations of the brightness of bulbs independently during the earlier experiments leading to fragment 8 (Figure 35).

**Table 17**      *Analysis leading to the fragment, Adding more bulbs dims all bulbs.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
<p>T: What happens, if I connect two bulbs to this battery, and only one to this one. Do they light as bright or does some bulb look brighter than others?                      L: I know.                      N: I don’ t know.                      Mi: I don’ t know.                      L: If you have two (bulbs in series), they look worse. Because I saw a moment ago, when we switched on one bulb, it was bright. But when we switched on two bulbs, they were both pale.</p>	<p>Two bulbs light dimmer than a single one alone.</p>	<p><b>Adding more bulbs dims all the bulbs (5)</b></p>

*Fragments 5→6→7: prequantification and theoretical explanation*

During the second lesson the small group expressed three fragments of different levels of external representations of the electric current. In Figure 37 these fragments are classified into different categories to emphasise their different natures and backgrounds. Fragment 5, which was described above in the context of the second fragment path is based on the

hypothesis. Two other fragments are *electric food divides between the bulbs (6)* and *the brightness of the bulbs as a measure of the electric current (7)*. The small group expressed fragment 6 during the experiments (RC) on adding more bulbs to a circuit. The electric food was a tool used to explain the varying brightness of the bulbs in different connections:

- Has the electric food finished off this (battery)? I suppose so.
- Maybe there are so many bulbs, that it is not enough (electric food) for all of them?

*Small group*

Fragment 7 was expressed after experiments with adding more bulbs to a circuit. It appeared in the context of starting an OPT (open problem task) of comparing the properties of two different batteries. In this phase the small group had reached the level of prequantification in its process of representing; in the discussion it was manifested that the brightness of similar bulbs can be applied in comparing the electric current in different electric circuits.

**Table 18**      *Analysis leading to the fragment, Brightness of the bulb as a gauge of the electric current.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
L: We will just construct that kind of next to it, and then we will compare. T: What will you compare? N: We will see, which one is brighter. L: Yes. T: What does the brightness of the bulbs tell us about the quantity of the electric current? L: Well, it tells us that the one which is brighter has more electric current.	Brightness of a bulb tells the quantity of the electric current.	<b>Brightness of the bulb as a measure of the electric current (7)</b>
N: There is more (current) now. L: Yeah, look at it. It has more.	Comparing the electric current	

*Fragment path 7→8→9: Electric current*

Using the brightness of the bulbs as a measure of the electric current was a strengthening external representation of the small group. Doing varying experiments with different numbers of bulbs in the circuit, comparing brightness, and discussing in the group with the

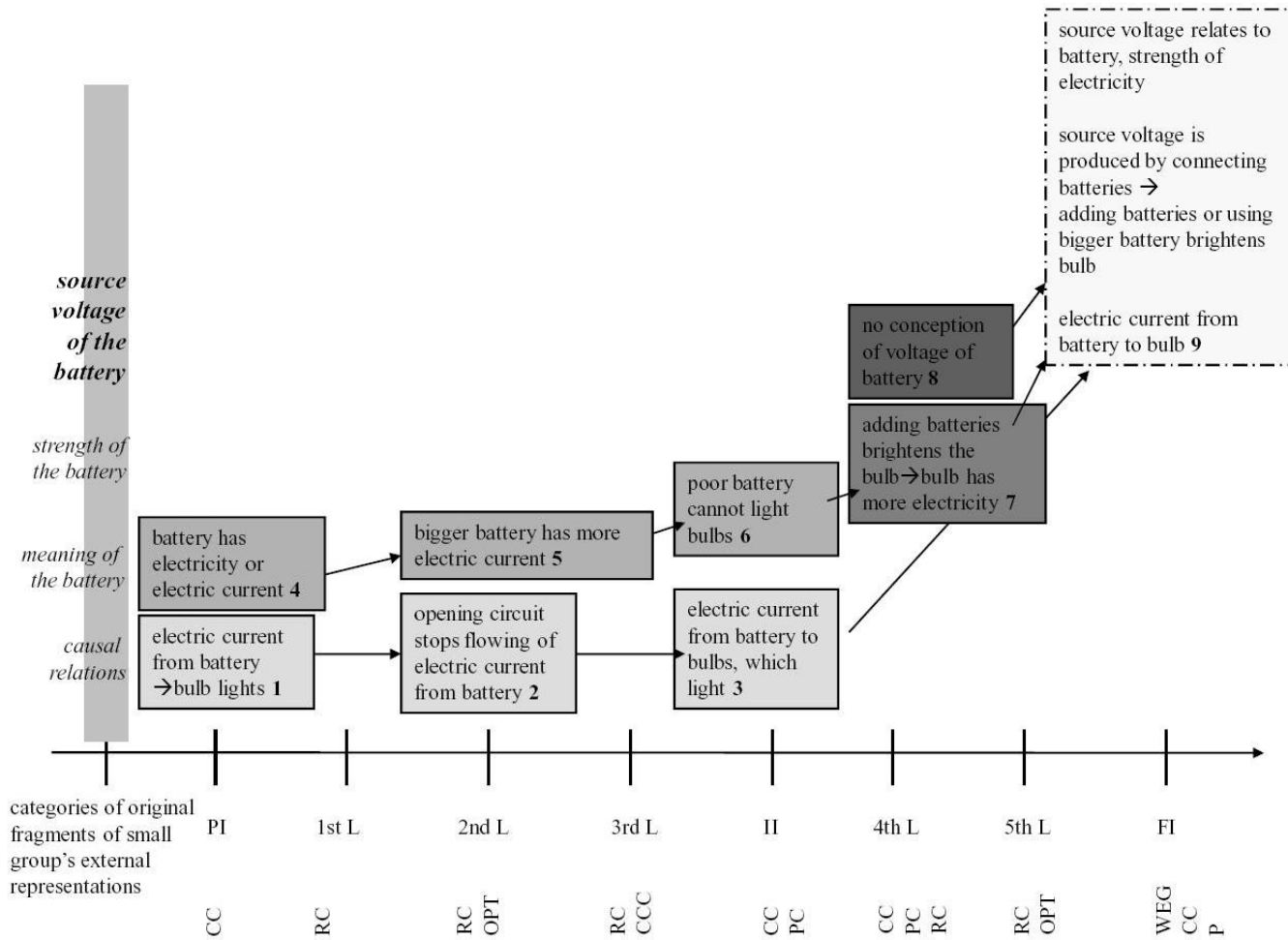
teacher (cf. the approach of learning in this study, section 3.4) made it possible to further the model of the originally unknown brightness-property of the bulbs to the level of the prequantified concept of a electric current with its own empirical law.

Fragments 7 and 8 are placed at the same level in the fragment map of the electric current (Figure 37). This means that they stand for a similar kind of understanding of the concept, so the fragment 8 *brightness of bulbs manifests equal electric current*, which was expressed during the 3<sup>rd</sup> L in context of CCC (claim card competition), only confirmed the earlier fragment.

The small group's final level of the external representation of the electric current was concluded in the intermediate interview (II), which charted their conceptions by means connection cards (CC) and picture cards (PC). In these discussions the group expressed fragment 9, which includes both the physically correct and less correct parts: *the brighter the bulb the bigger the electric current, bulbs light simultaneously, electric current moves quickly from the battery, current is divided between the bulbs*.

### **7.3.3 Results: Small group's external representations of the source voltage**

The modelling process of the external representation of the source voltage extended to the whole teaching experiment. Although the first half of the teaching experiment focused on experiments on the electric circuit and the electric current, they also outlined the modelling process of the source voltage: the meaning of a battery to the electric circuit was discussed in the PI and batteries were used in the experiments during the first three lessons. However, the primary lessons for modelling the source voltage were lessons four and five. In addition the final interview also included special questions concerning the source voltage. During the second half of the teaching experiment experiments – adding batteries to an electric circuit, connecting batteries in opposite polarity, changing the place of battery in the electric circuit, constructing a dollhouse-electrification, and solving the problem of a broken pocket lamp – were done. The types of experiments used were PC, CC, RC, OPT, WEG, and P, see the horizontal axis of Figure 38.



**Figure 38** The fragment map for the external representation of the source voltage.

As discussed above the modelling process of the source voltage was divided into a spontaneous part during the first three lessons, and to a more guided part during the 4<sup>th</sup> and 5<sup>th</sup> lessons. Moreover there were interviews PI, II and FI, which also included the themes of source voltage and batteries. Due to the different phases of modelling the source voltage, the fragment map (Figure 38) includes four not simultaneous fragment paths, which overlap less than the paths portrayed earlier in figures Figure 35 and Figure 37.

The fragments, which emerged during the content analysis, have been classified into four categories: 1) *causal relations*, 2) *meaning of the battery*, 3) *strength of the battery*, and 4) *source voltage of the battery*. The first of the categories deals according to its name with the causal relations of the circuit. Therefore, categories 2-4 stand for comparative fragments of different levels.

*Causal relations: fragment path 1→2→3*

Understanding the main causal relations is a basic requirement in a modelling process. In the case of DC-circuit phenomena the relation between the source voltage, or at least the battery, and the electric current is a fundamental part of the external representation of the source voltage. The fragment path 1→2→3 pictures the small group's external representation of the causal relations of the DC-circuit phenomena. According to the small group the battery is the source of the electric current (1, 2, 3). This fragment of external representation of the source voltage appears unchanging in the talk of the group, and it is used in explaining the following phenomena: 1) bulbs light because of electric current flowing to them from the battery (1 and 3) and 2) bulbs go out because of stopping the flow of electric current from the battery (2). Table 19 below gives an example similar to fragments 1, 2 and 3.

**Table 19**      *Content analysis leading to fragment 3, Electric current from battery to bulbs, which light.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
M: Because that battery and those wires no longer bring the electric current to the bulb, it goes out.	The electric current from the battery via wires to the bulb	<b>Electric current from battery to bulbs, which light (3)</b>
L: They go out in a nice way, so that the electricity goes, whoosh. It goes away.	The bulb goes out, when the electricity leaves from it.	
R: Why does the bulb light? M: Because the battery gives the electric current to it.	The battery gives electric current to the bulb.	

*Meaning of the battery: fragment path 4→5→6*

The fragment path *Meaning of the battery* stands for the first phase of prequantitative knowledge in the process of external representing the source voltage. This fragment path

formed during the first three lessons, when the source voltage was not yet at the focus of learning. Fragment 4 was expressed during the preliminary interview as an answer to a question concerning the meaning of the battery in the electric circuit. A typical part of the talk was the following:

Teacher: What do you think, Milja? Will the bulb light?

Milja: No.

Matti: Because there isn't a battery.

Laura: Because there isn't that source of electricity (in the circuit).

*Small group*

From this and similar representations expressed it was concluded that at the beginning of the teaching experiment the small group understood the battery as a source of electricity, so the fragment was named as *Battery has electricity or electric current*. During the next three lessons the small group got lots of experiences of connecting bulbs in series. The batteries used in these experiments were 1.5 V and 4,5 V ones. These were particularly the first experiments that made the small group compare properties of different batteries.

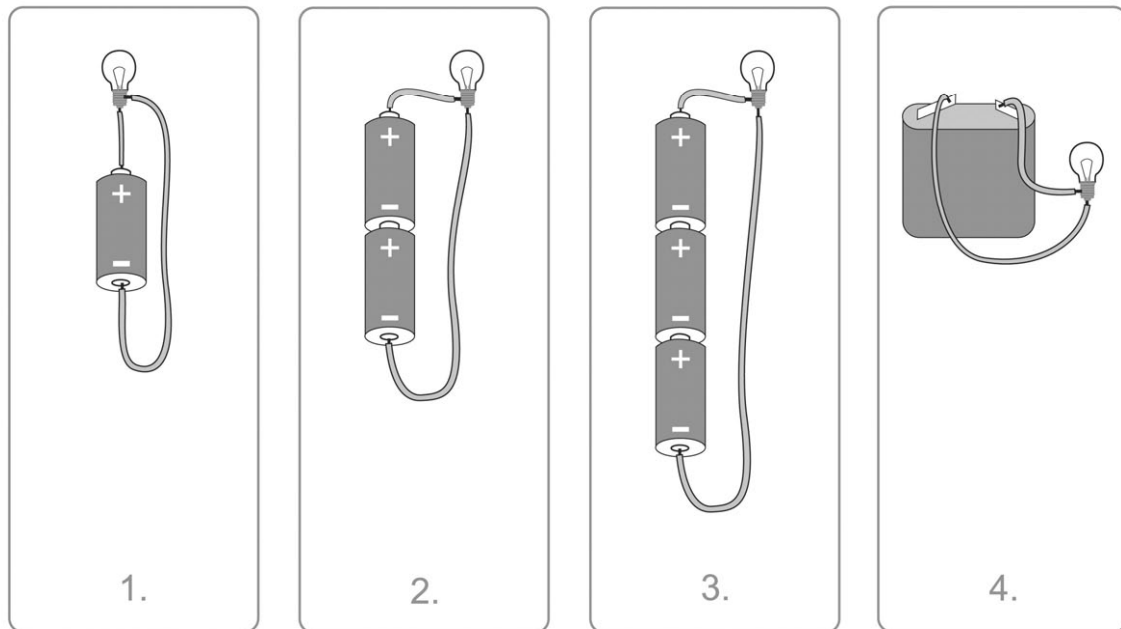
**Table 20** *Fragment 5 of the external representation of the source voltage of the battery.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
M: We learnt that when we have... N: Where two bulbs are lighting. L: That when there is the bigger battery, and then three bulbs are lighting. And by that smaller battery they don' t.	More bulbs are lit by a bigger battery.	<b>A bigger battery has more electric current (5)</b>
T: Do you remember why the bulbs were lit by that bigger battery? N: It was more aimed for that use. Teacher: It can be, but... L: It was bigger. T: Yes. L: It had more electric current, so it was enough for every (bulb).	A bigger battery is used for more bulbs.  A bigger battery has more electric current, which is enough for every bulb.	

As it is described in Table 20 fragment 5 was expressed in a discussion with the teacher at the beginning of the third lesson when the teacher asked what kinds of things the small group had learnt the last time. The small group seemed to be in agreement with the property of the battery: *a bigger battery has more electric current*. This fragment of the external representation of the source voltage appeared also in the intermediate interview, when the small group used an expression *A Poor battery cannot light bulbs (6)* in differentiating batteries from each other. So, the small group had actually formed independently the prequantitative relation between different batteries.

*Strength of the battery, fragment 7*

The fourth lesson included experiments of adding several batteries in series. Batteries were added in series both by connection cards at the beginning of the lesson, and later by real connections. Also picture cards (see Figure 39 below) were used to help the small group to think of a new situation with a different number of batteries in series.



**Figure 39** *Picture cards used to chart the small group's external representation of adding more batteries in series. What happens if another battery is connected to circuit 1? What if a third battery is added? The batteries are identical. What happens if there is only one battery in the circuit as shown in number 4?*

Fragment 7 is a hypothesis, which the small group expressed before the real connections of adding more batteries in series. The result *Adding batteries brightens bulb → bulb has more electricity* is a logical continuation to the fragment path 4→5→6 described earlier. Thus, it appears that for the small group the strength of the battery is a natural way of perceiving the DC-circuit phenomena. Though fragment 7 again includes the incorrect theoretical explanation of the battery as a source of electricity (or electric current), the fragment shows quite a well-developed empirical based external representation of the strength property of the battery. The same kind of picture of

understanding the strength of the battery also appeared during the last lesson when the small group worked with open problem tasks. For more discussion in context of fragment 7 see Appendix 8: Adding batteries brightens the bulb.

**Table 21** *Fragment 7 of the external representation of the source voltage of the battery.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
<p>T: Could it be possible to add more batteries to this kind of circuit? Small group: [everybody nods]</p>	<p>It is possible to add batteries to a circuit.</p>	<p><b>Adding batteries brightens the bulb → the bulb has more electricity (7)</b></p>
<p>T: What would happen in this circuit? There are two batteries now. N: Well, I don't know, but I think that the bulb will brighten more. It has more electricity now. M: That number two and three, I have thought that the bulb will light brightly.</p>	<p>Adding batteries brightens the bulb. The bulb has now more electricity.</p>	
<p>L: I am thinking about this number four, I suppose that the bulb would light as brightly by this as by two of these little poorer. T: Yes. What do you think, in which circuit would the bulb be as bright as with this battery (number 4)? If there would be one of this of battery (number 4), so how many of these kinds would be needed (number 1) to get as bright a bulb? L: [shows number 2] M: Three. N: Two. Mi: Two.</p>	<p>Batteries can be added: two or three poorer batteries equals one better battery.</p>	

*Fragment 8: Voltage?*

Fragment 8 is separated into its own fragment, because it represents an interesting detail of the small group's knowledge structure of the source voltage of the battery. The small group had *no conception of the voltage of a battery (8)*. The role of the battery was just to act as a store of the electric current, so there was no need for a special property of the battery. The size of the battery seemed to be related to its capability to storage the electric current.



*Source voltage of the battery, fragment 9*

Fragment 9 stands for the small group’s final external representation of the source voltage. To the external representation has been collected all the main aspects of the source voltage, which the small group expressed during the final interview. If started from the top (see fragment 9, Figure 38), the first part of the external representation is the following: *source voltage relates to battery, strength of electricity*. This kind of representation appears from the following discussion:

**Table 22**      *Source voltage relates to battery.*

ORIGINAL TALK	REDUCED EXPRESSION	FRAGMENT
T: What does the voltage mean, do you remember? Mi: It is that current. L: But no it that ... voltage affair... T: What is the voltage relate to? T: Milja? Mi: Nothing. Teacher: To what part of the circuit does the voltage relate? L: Was it to that battery? No!! T: Yes, it was. Mi: Is it how strong the electricity is... or that? T: Niko? N: It is that, what this is...it is battery’ s current...or it.	voltage is current, no  voltage is related to the battery  how strong the electricity is  voltage is the battery’s current	<p><b>Source voltage relates to the battery, strength of electricity (9)</b></p>

As the discussion reveals, it was still quite difficult in the end of the teaching experiment for the small group to distinguish the source voltage from the electric current. Moreover, it seemed to be difficult to precisely localise the source voltage. However the language used in the small group reveals that to the external representation contains a mental picture of the source voltage, which is related to the battery, and according to this image, the source voltage measures the strength of electricity.

The next part of the external representation (9) discusses the idea of strengthening the property of the battery. Firstly, the source voltage is produced by connecting the batteries in series. Secondly, the property can be strengthened either by adding more batteries or using bigger batteries. Here the small group has achieved the empirical law between the number of batteries in series and the brightness of the bulb.

The last part of the external representation (9) includes the small group’s conception of the causal relations of the electric circuit. Although the external representation is incorrect,

when it describes the role of a battery as a source of the electric current instead of a property of a battery to cause the electric-current phenomenon, the external representation however includes the picture of the direction of the causal relations. According to the small group the battery is the starting point and the lighting of the bulb is an effect-phenomenon.

## 7.4 The teacher's role during the teaching experiment

During the teaching experiment the teacher's role was strong as discussed earlier in section 4.3.2.1. The role was to 1) to pull together and guide small group's discussions and thinking, 2) to name and explain observed phenomena and developing concepts, and 3) to inhibit or correct large deviations from the truth in the small group's thinking.

The role of pulling together (1) appears from Appendix 5: Analysis leading to the fragment "bulbs in series light because of the electric circuit", when the teacher points out the electric circuit once again to the small group:

T: When there are both bulbs light, there must be electricity everywhere. And look at here, when I broaden this circuit a little. Do you notice that this really is this kind of electric circuit?

While going on teacher named (2) the observed electric circuit with the following utterance:

T: Yes. This is called an electric circuit, when all of these (components) are connected.

The teacher's correcting role (3) appears in Appendix 7: The teacher's guiding role, where she rebuts the small group's erroneous external representation of plus- and minus electricities shortly by commenting:

T: Well, there is nothing plus- and minus electricity (in the circuit), anyway...but only the same electricity.

However, the teacher does not offer a new explanation, but gives the small group a new chance to think about the situation again.

## 8 Trustworthiness

Instead of reliability and validity, which are originally criteria of trustworthiness created for quantitative research, the following special trustworthy criteria have been proposed for qualitative research: *credibility, transferability, confirmability and dependability* (Denzin and Lincoln 2000; Lincoln and Guba 1985; Tuomi and Sarajärvi 2002). Credibility refers to different views of the truthfulness of results. Credibility depends on the researcher, her or his ability to collect as truthful data as possible, and to reconstruct the research subject as close to the original form as possible. Although the purpose of a qualitative research is not to produce entirely transferable and generable results, it is however important to prove the usefulness of the study. By the confirmability of a study we mean that the study is true to the data-respectful approach that is to say; the results are based on data instead of the conceptions of the researcher. Trustworthiness in this respect can be improved by comparing the results to other similar research, and by allowing a co-researcher to evaluate the analysis and methods used. It is also important to depict the analysis so that the reader can follow reasoning. The dependability of a study is a measure of how different aspects of changing situations in a study are taken into account. Dependability can also be increased by following the main principles of scientific research. Here the above described criteria are discussed from the stand point of data and content analyses.

The *credibility* of results depends on the truthfulness of the data, which relies on the trust between the researcher and the people being researched. Also the way the data is collected and observations are made have an effect on credibility (Denzin and Lincoln 2000, 20; Lincoln and Guba 1985, 301). However, the main criteria for credibility are functions of researcher herself. The grounds for doing this study were pragmatic paradigm (section 4.1) and the adopted new Experimental-centred representation was the approach to learning (section 3.4), thus these views have guided the research.

This research used the original historical articles of DC-circuit phenomena (see section 4.3.1). Data for the teaching experiment was mainly videotaped data (see section 4.3.3), which collected with two camcorders. The criteria for choosing the member's of the small group are described in section 4.3.3 and in Appendix 1. To make the situation close to the children's world the teaching experiment included different kinds of tasks: plays, games and problem tasks. The empirical data was collected in different forms like from typical negotiation situations, teaching situations, problem situations, drawing situations and game situations to give all the learners possibilities to show their progress.

The pupils worked mainly in small groups, and sometimes in pairs. To increase the credibility, the pairings during the lessons and interviews were also changed occasionally. The climate of the teaching experiment was good from the very beginning thanks to the careful design. The small group worked well in a relaxed fashion, and seemed to concentrate well and keenly on their learning. The interviewer and the teacher worked as a researcher-pair. The two individuals collaborated beforehand in designing the work, and during the teaching period in continuous feedback discussions between the lessons and interviews. It was also possible for the interviewer to ask or comment during lessons if necessary, and vice versa. By her continuous participation in the process the researcher could search for information, which was as authentic as possible.

In content analyses of historical data and the empirical data there are many authentic quotations and pupil's talk. The meaning of these quotations was to increase the *transparency* of the analyses. See for example section 5.3.2 (historical data) and Table 15 (empirical data).

The external representations of DC-circuit phenomena described the learning process of one small group. Thus, it is not possible to expect that the results would be *transferable* as such. On the other hand, the pupils that were chosen for the teaching experiment represented average pupils, this fact that gives room for generalising the result to some extent. This view was also described in section 4.2 in discussing research method. Furthermore, the results uncovered typical theoretical explanations reported earlier (see section 9.2), which also give some possibilities for generalising. The results also encourage using the designed teaching experiment in teaching and learning DC-circuit phenomena.

On the other hand, a small group consisting only of average pupils, has not proven to be such fruitful learning environment than the group of dissimilar learners. According to Bennet et al. (2004, 4), particularly the dissimilarity of the small group members in terms of their domain-specific understandings improves pupils' understanding. However, the results of the second research question showed that the present arrangement was a particularly good learning environment. So, according to this research, good skills of discussing and arguing are the most important aspects for small group learning.

To underpin the *confirmability* of the analyses, the phases of content analyses were checked by and discussed with other co-researchers. The content analyses of historical data (research question 1) were checked by the censors (Kallunki 2001). The seven categories describing the level of pupils' talk (research question 2.1., section 7.2.1) were checked by three co-researchers. The number of categories and their order were discussed many times, so that the number of categories were reduced from eleven to seven categories. The categorisation was renewed at intervals of a few weeks. This part of the study was also published in a refereed Girep-Epec Conference 2007 Proceedings Book (Kallunki 2008). The content analyses of research question 2.2. were discussed several times by the co-researchers. These discussions dealt with the phases of analyses and representing the fragment maps (see Figure 35, Figure 37 and Figure 38). Finally, the whole process of content analyses in the third phase of the study was explained in detail to a co-researcher. The confirmability of the empirical data was increased by datatriangulation (Patton 2002, 306), i.e. by gathering data from the lessons and interview periods (see section 4.3.3).

A matter affecting the *debendability* of the study was revealed in the preliminary interview concerning the experience of constructing an electrified lighthouse. In spite of the precautions in pupil selection described in section 4.3.3, it was revealed that of the third-graders all except one had recently constructed an electrified lighthouse which included a connection of the electric circuit during their crafts lesson. This experience appeared in the talk of the small group especially during the preliminary interview, and clearly acted as a starting point for the children's thinking. However, this experience did not appear to lead their thinking during the following lessons and the interviews. This recent experience with the lighthouse however affected the small group's initial external

representations of the electric circuit: three of four third-graders understood that to light a bulb both terminals of the battery had to be connected to the electric circuit, whereas the corresponding proportion of the fifth-graders was two out of four.

The trustworthiness of this study can also be reviewed from the standpoint of the *characteristics of good design research*: 1) central goals of designing learning environments and developing theories of learning are intertwined, 2) development and research take place through continuous cycles of design, enactment, analysis, and redesign 3) research leads to shareable theories that help communicate relevant implications to practitioners and other educational researchers, 4) research accounts for how designs function in authentic settings, and 5) research relies on methods that document and connect enactment to outcomes of interest (Design-Based Research Collective 2003, 59).

The second phase of the study (chapter 6), represents a phase of intertwining and aggregating the goals of designing and theories of learning. The chapter and especially Figure 27 includes a detailed description of different factors affecting the design process and the design solution itself. Although the study does not include many iterative cycles of designing, it however clearly uses the basic properties of design research: the phases of research and design and research form a dialectical process of designing work (section 4.2.2). The implications of results are discussed in chapter 9. This chapter also includes a discussion of the practical advantages of the study. In section 3.4 the new approach of learning, the Experimental-centred representation, which describes learning more comprehensively than earlier approaches, is described. The accounts for how the design solution functions in authentic settings are described in chapters 7 and 9. The methods that have been used, are explained in chapter 4.

The study's value can also be evaluated from viewpoints of *improvement* of teaching and learning (Design-Based Research Collective 2003, 7) and *usefulness* (Edelson 2002, 118). The starting points of this study were both scientific and politico-educational (section 1.2), thus the goal was to produce knowledge that can improve and be useful for teaching and learning. These aspects are discussed in the Summary (chapter 9).

## 9 Summary

In the study, the development of models of DC-circuit phenomena in doing science and learning was researched. The study was carried out as design research, including phases of examining the development of historical models of DC-circuit phenomena, designing the teaching experiment, and realising the teaching experiment. In the study, learning and doing science were studied via a new Experimental-centred representation –approach (see section 3.4), which unites an empirically oriented perceptual approach and a theoretically orientated model-based reasoning –approach. This new approach meant considering 1) the pupils' earlier external representations, 2) the teacher's teaching model, and 3) nature phenomena as affecting factors in the learning process. From the pupil's point of view, learning physics starts from his/her earlier representations. According to the approach, the learning situation in the classroom is a mixture of empirical operations like experimenting, observations, perception, and prequantification of nature phenomena, and modelling operations like explaining and reasoning. These operations are understood to take place in small group discussions and argumentations as a part of higher-order thinking. Furthermore, also the intuition of the human mind plays an essential role in learning.

The study is an important addition to the science education research, and particularly to the research of learning DC-circuit phenomena. The results of the study challenge previous researches (see section 1.2.1) of the difficulty and abstractness of DC-circuit phenomena. In this study, the learning process of the abstract subject matter has been supported by using a teacher-guided small group learning environment, promoting pupils' modelling by experiments, and utilising historical modelling processes as a source of inspiration in planning the teaching experiment. Thus, pupils' own talk and especially incorporating talking about experiments to the modelling process have stimulated their learning.

By using the enlarged framework of the model as an analysis tool, we obtained a deeper understanding of small group's learning. The results uncovered empirical-centred progress in the small groups' learning, and presented the learning of DC-circuit in a more optimistic light than the typical mental model researches.

### 9.1 Summarising the results for the research questions

*How did the historical models of DC-circuit phenomena develop in Volta's time?*

The developing of the historical models of DC-circuit phenomena in Volta's time was analysed in the first phase of the study by content analysis. The historical modelling process was showed to include perceiving a new phenomenon, a continuous electric-current phenomenon. The modelling process also included conceptualising all the DC-circuit phenomena relating to the electric-current phenomenon. Although the historical models were based on the Pile and the first experiments of it, they were first triggered by Volta's and Galvani's model debate about the origin and the nature of electricity. Different

identifying, perceiving, comparing and varying experiments formed a picture of the DC-circuit phenomena. The analysis uncovered that Volta's conceptions of the DC-circuit phenomena can be described by three qualitative historical models: 1) the model of a closed circuit, 2) the model of electric fluid/current, and 3) the model of contact electricity.

The model of closed circuit (see Figure 23) represented the Pile, the conductor and the electric current as essential parts of the electric circuit. Furthermore, according to the theoretical explanation of the closed circuit, the circuit was understood as a route of electric fluid. The model of electric fluid/current explained the observed electric-current phenomenon. The model included a conception of causal relations: the electric current was understood as a cause-phenomenon to different effect-phenomena like chemical phenomena. Comparisons of the effect-phenomena formed a new property, the strength of the electric current. The historical model of electric fluid (see Figure 24) also included the first empirical law, which explained the relation between the length of a wire and strength of the effect-phenomena of the electric current. Theoretical explanation of the phenomenon was a continuous and instant flow of a fluid-like current-entity. The model of contact electricity (see Figure 26) extended the historical picture of the DC-circuit phenomena: the Pile was understood to be the cause of the electric current, and the ability of the Pile to generate the electric current was recognised as the empirical law of the contact electricity model. According to the model, the metal pairs of the Pile set in motion the electrical fluid, which consequently falls into disequilibrium.

#### *The design solution*

In the study the design solution was divided into three sections (see Figure 27): 1) the teaching model that embodies the subject matter outcome of the designing process, 2) the learning environment that includes the pedagogical aspects of the solution, and 3) the teaching experiment itself, which is the structural outcome of the designing process. In designing the teaching model, the historical models, pupils' external representations, subject matter needs assessment, and consensus models of DC-circuit phenomena were utilised. Also the designed Experimental-centred representation –approach was utilised as a didactical theoretical background. As a result, the teaching model included influences of historical experiments; especially, the empirical part of historical concept formation was stressed, so the teaching model included lots of experiments that compared properties and stressed causal-relations in the circuit. As in the historical models, the electric circuit played a crucial role in the teaching model. The ideas from pupils' external representations concentrated on keeping in mind the different erroneous representations of pupils while designing the experiments for the teaching experiment. Also, the subject matter needs assessment supported the basic identifying and comparing experiments with simple electric circuits.

Furthermore, to underpin the subject matter outcome, the design solution also took into account the pedagogical aspects of learning. In this phase the outcomes from the pedagogical needs assessment and the pedagogical theoretical background were used. Both views emphasise the pupils' active roles in learning, and also closeness to children's world is highlighted. In this study, to underpin especially pupils' active role in modelling,

the learning environment was planned to include talk-activating tools – like games and plays – and the learning itself to be realised as small group learning. The special invention of the study, to activate the small group's thinking and talking, was the developing of connection cards. By using these cards it was possible to construct the same connections as those with the real components, but the pupil's could not know if their card connections really worked. This kind of situation makes the discussion more democratic and is supposed to activate talk.

The last part of the designing solution was the teaching experiment itself, which is described as a structural outcome. In realising the teaching experiment, the above outcomes were taken into account. The teaching experiment consisted of three interviews and two small group learning periods. The interviews charted and concluded the external representations of the small group. During the first small group learning period (lessons 1, 2 and 3) the subjects were the electric circuit, the electric current and comparing current strength. In proportion, the second learning period (lessons 4 and 5) included themes of the source voltage and comparing the magnitude of the source voltage. Furthermore, during the last lesson all what had been learnt was applied in doing the last tasks.

Using the small group as a learning environment turned out to be the right decision. The talking and thinking in the analysed third-grader's small group was lively, and towards the end of the teaching experiment all the pupils were encouraged to express their own opinions and negotiate with others. As has been stated earlier the meaning of language is important to learning. By bringing the learning environment as close as possible to the children's world and by avoiding too scientific language in the phases of identifying the new phenomena, the small group learning proved to be a fruitful environment for developing the external representations. As the analysis showed the small group really constructed its external representations together. The pupils listened to each other's opinions and either agreed or disagreed with them. However, it has to be taken in mind that the role of the teacher was also crucial in the form of guiding, asking the right questions, naming the perceived concepts, and summarising the learnt subjects.

The innovation of this study, the special connection cards was the best functioning tool in activating the thinking process in the small group. Using the cards in contexts of making hypotheses of new connections really made the small group's thinking visible and started the learning process.

*How will the small group's external representations of DC-circuit phenomena develop during the teaching experiment?*

Developing of the small group's external representations of DC-circuit phenomena during the teaching experiment was gone about with two sub questions: 1. *What kind of talk exists in the small group's learning?* and 2. *What kinds of external representations for DC-circuit phenomena exist in the small group discourse during the teaching experiment?* In the first phase of the analysis the small group's talk during the teaching experiment was analysed by charting the level of cognitive processes to uncover any possible higher-order thinking requiring external representations. In the content analysis we found seven categories of pupils' talk (see Table 11) of which the two highest – creative talk and explanatory talk – clearly included the external representations of the pupils. Also the third



level of talk, thinking aloud, could be regarded at least partially, to contain ideas of external representations. As a special result of this phase it was seen that in context of doing experiments with the connection cards (see Figure 33) the levels of talk were higher than with real equipment (see Figure 34), and this talk included more external representations of the small group.

From the basis of the first sub question the analysis was widened to focus on the knowledge constructing during the teaching experiment. The content analysis for developing the small group's external representations of DC-circuit phenomena during the teaching experiment resulted in three fragment maps of the external representations: 1) the electric circuit (see Figure 35), 2) the electric current (see Figure 37), and 3) the source voltage (see Figure 38). The maps consisted of separate boxes arranged into categories and placed according to the progress of teaching. In these maps separate boxes describe fragments of developing external representations.

The fragment map of the electric circuit describes the small group's developing external representation of the electric circuit. Due to their earlier experiences in their technical work lessons, the small group succeeded well in connecting a simple circuit during the preliminary interview. However, their original external representation proved to be imperfect: the structure of a bulb was not clear as a part of a circuit, lighting of more bulbs would not be possible without several batteries because of two different electricities, and the circuit would not include electricity without a bulb. Especially fragments 3 and 5, *Need for plus- and minus electricities to light a bulb* and *Lighting of more bulbs is not possible without several batteries* were problematic. The picture of the circuit widened during the experimental lessons, and particularly the second lesson was a turning point in their development of the external representation of the electric circuit: after the experiments with real connections with several bulbs in series the small group found a new explanation model, thus fragment 8 *Bulbs in series light because of the electric circuit* showed the clearest step forward towards more a scientific model for the electric circuit.

In the second fragment map, the development of the external representation of the electric current, the modelling process starts from two categories: brightness of the bulb and lighting order. There was development, first initiatively and then guided, in the category of the brightness of the bulb. Fragment 4, *Brightness as a property of the bulb*, appeared spontaneously in the discussions before the proper experiments of comparing the brightness. The other interesting phase of modelling happened during the second lesson, when the small group expressed three fragments of different categories. These fragments – *Adding more bulbs dims all bulbs* (5), *Electric food divides between the bulbs* (6), and *Brightness of the bulb as a measure of the electric current* (7) – express a hypothesis, an explanation and the first prequantitative bit of knowledge. Furthermore, fragment 6 is an interesting example of the small group's use of language in the modelling. The concept of food as a parallel to the electric current illustrates their lively thinking. The other main path of the modelling process deals with the lighting order of the bulbs. There was also development in this category, but the information formed was incorrect.

The development of the external representation of the source voltage is interesting in two respects. Firstly, the fragment path 4→5→6, *Battery has electricity or electric*

*current, Bigger battery has more electric current, and Poor battery cannot light bulbs,* developed before the source voltage was the focus of learning. The path is again an example of the small group's self-ruling modelling: along with guided modelling of the electric circuit and the electric current the small group also autonomously developed its external representation of the source voltage. From this standpoint fragments 7 *Adding batteries brightens the bulb* → *bulb has more electricity* and the final fragment 9 are only correctives to the self-ruling modelling, or at least the autonomous developing of external representations acted as a good starting point to the process. On the other hand, the second interesting point in developing the external representation was the weak development of the concept source voltage itself. Although the prequantitative understanding of the battery's purpose and its strength were well developed, the concept of source voltage was surprisingly difficult to disentangle from the electric current. The relation between the voltage and the battery seemed to not be organised until during the final interview. In parallel to modelling the purpose of battery, there also took place a modelling of the causal relations in the circuit. However, this fragment path did not include any notable development. The erroneous external representation of the battery as a source of the electric current tenaciously existed in the talk of the small group.

## **9.2 Comparing the external representations found to earlier pupils' representations of DC-circuit phenomena**

Earlier reported pupils' external representations (see section 6.2) have mainly focused on theoretical explanations of DC-circuit phenomena, which in this study were understood only as one fragment in the whole framework of model. In this study, also all qualitative conceptions of pupils' belonged to the external representation; expressed conceptions on the basis of observation and perception, understanding causal relations, forming gestalts, doing prequantitative experiments, and finding concepts and empirical laws between them, and making theoretical explanations could all form fragments of external representations. Here the similarities between external representations of earlier reported studies and the results of this study are paralleled, when possible.

There exist few interfaces to the earlier reported external representations of DC-circuit phenomena in the fragment maps of the electric circuit, the electric current and the source voltage. In the fragment map of the electric circuit these interfaces are in fragments 3 and 4, *Need for plus- and minus electricities to light a bulb (PI)* and *Bulbs light when both electricities circulate to it (1<sup>st</sup> L)*. These two fragments with the very same contents can be paralleled to Kärqvist's two-component model (K2), Osborne's and Freyberg's clashing currents or Borges' and Gilbert's electricity as opposing currents (BG 2). Thus the external representation of two opposite electric currents as a requirement of lighting a bulb seems to be a general way of thinking among children, and it is also found in this study of younger children. The picture fits Borges' and Gilbert's observation that this kind of model is typical at the beginning of instruction (see Table 8). Furthermore, according to Kärqvist's model classification the conception of two electricities is placed on the second lowest class in the six-grader classification.

The fragment map of the electric current includes two fragments that are commensurate with earlier models. Firstly, *Electric current moves quickly to light the bulbs simultaneously* (fragment 2, 3<sup>rd</sup> L) includes the conception of a current that flows from the battery to the bulbs. This conception is characteristic to all but K6, which is Ohm's scientific model of the phenomenon. In models K1-K5 something (electric current or energy) flows from battery to bulbs lighting them. Fragment 2's external representation is in fact an interesting mixture of the small group's earlier theoretical explanations and real observations of the lighting of the bulbs. The fragment gives a solution to the contradiction of battery as a source of electricity and simultaneously lighting bulbs. Thus, fragment 2 is a development in the theoretical explanation of the nature of the electric current.

The other interesting fragment in the fragment map of the electric current is *Electric food divides between the bulbs* (fragment 6, 2<sup>nd</sup> L). The fragment was expressed during experiments (RC) of adding more bulbs to a circuit. The electric food was a tool used to explain varying brightness of the bulbs in different connections. The fragment has a close connection to Kärqvist's constant current source model and Osborne's and Freyberg's sharing model. The idea of these models is that the bulbs share the electric current, which one bulb would otherwise get. In this study fragment 6 has the same content. The image of electric food is used in the same ways as dividing food in a fair way in a family.

The fragment map of the source voltage also includes one similarity to the earlier models. While processing the causal relations of the electric circuit the small group repeatedly expressed the fragment *Electric current from battery to bulb* (fragments 1, 2, 3, 9, PI, 2<sup>nd</sup> L, II, FI). Although the fragment includes the correct idea of the battery as a cause of the DC-circuit phenomena in a circuit, it also includes a typical erroneous external representation of the battery as a source of the electric current (K1 and BG1).

### **9.3 Comparing external representations to historical models of DC-circuit phenomena**

In designing the teaching experiment we used information of the development of historical models of DC-circuit phenomena, thus there were lots of structural similarities like similar experiments in these two learning affairs. However, the learners were absolutely different: while Volta represented an expert with a spontaneous interest in developing the Pile and to understand DC-circuit phenomena, the small group typified normal third-graders and novices.

The basic content of pupils' external representation of the electric circuit and the corresponding historical model are similar including understanding of the parts of the circuit. In the case of Volta the meanings of different parts of the circuit are clearly on a higher level including classification to cause, intermediate and phenomenon, while the small group did not understand the nature of the circuit nor the structure of the bulb at the beginning of the teaching experiment: *No electricity in the circuit without the bulb (6)*, *No conception of the structure of the bulb (1)*. However, the biggest problem in development of the small group's external representation of the electric circuit was the incorrect

conception of two currents, *Need for plus and minus electricities to light a bulb (3)*. In development of historical models, there was also earlier a conception of two classes of electric currents, but this was not a problem for Volta, whose conception of electric current was that of a single-current (see section 5.3.1).

In the models of electric current there are fragments of the nature of current that are similar to each other. The nature of the electric-current phenomenon is slightly different. 1) According to historical model, the electric current is *Continuous and instant flow of a fluid-like current entity*. Every body has this fluid-entity, and it starts to move, when an external mover excites it. In the small group's representation, the electric current is a substance like *electric food (6)*, which *moves quickly to light the bulbs simultaneously (2)*. Thus, the difference is not so much the nature of the current as its origin. The small group paid no attention to the continuity of the phenomenon, which was very important in the historical situation. Comparing the strength of the electric-current, and its empirical law are characteristic to both the models. The small group started to do spontaneously comparisons of the brightness of the bulbs, but the teacher clarified the meaning of it. For Volta, however, the strength of the effect phenomenon was clearly in relation to the cause-phenomenon, the electric current. The empirical laws of the electric current are *The longer the conducting wire in a circuit the weaker effect-phenomena of the electric current (HM)* and *The brighter the bulb the bigger the electric current (9, small group)*.

In the case of the source voltage the causal relations differ to some extent. While the small group understood the battery as a source of the electric current, *Electric current from battery to bulb (9)*, for Volta the picture was clearer. The Pile or the bi-metallic pair is the cause-entity, which moves the electric current in bodies, and as effect-phenomena are observed sensations, contractions and chemical phenomena. The empirical law of the source voltage exists in both models: *The more metallic pairs in the Pile, the stronger the electric effects (HM)* and *Adding batteries brightens the bulb → bulb has more electricity (7)*. The historical model explains in more detail the utility present in the structure of the battery, but otherwise the laws are quite similar. The concept *Strength of electricity (9)* did not appear in the small groups fragments until the final interview. For Volta, by contrast, the corresponding concept the *strength of the electric power*, was fundamental and developed from the invention of the bi-metallic pair already before the Pile. In fact, the small group did not know anything about the concept voltage at all, whereas the electric current was used spontaneously from the very beginning.

The roles of empirical observations and perceptions, and theoretical explanations varied. Volta did experiments very systematically and explained his conceptions on the their basis. However, his starting point was to question Galvani's animal electricity model. The pupils' external representations were developed empirically, but there also existed the described theoretical fragments in them. If reviewed from the perspective of the development of theoretical explanations, the learning seems to be weak. In the case of the small group, the main point is however empirical learning. As described above, the external representations of DC-circuit phenomena include lots of remarkable development and the representations are much more functional in the empirical-based fragments.

## 9.4 What kind of knowledge did the study produce?

The study produces knowledge of the learning processes of third-graders in learning DC-circuit phenomena in a small group. The advantages of this study is the knowledge of the meaning of 1) different kinds of experiments with connection cards and real connections, and 2) small group learning, for the development of external representations. Furthermore, the study produced pragmatic information concerning the learning of DC-circuit phenomena: as a result are got data on the 3) essential phases and devised methods for teaching to promote the development of external representations. The important 4) developing processes of historical modelling of DC-circuit phenomena have a value as such, and they also served factors in designing the teaching.

By using 5) the Experimental-centred representation –approach as a guide in designing the teaching experiment, and 6) the framework of the model as a tool in analysing the empirical data, we obtained 7) the small group’s external representations, which were contentually rich. The results prove that modelling of DC-circuit phenomena include fragments of theoretical explanations as previously widely reported. In this study these theoretical explanations proved to be difficult to change, but there also took place some development as the analysis of the fragment *Electric current moves quickly to light the bulbs simultaneously (2)* showed. Along with theoretical explanations the analyses uncovered more empirically based fragments, which showed a real development in learning. These findings support our enlarging the field of modelling and also including some empirical conceptualisation processes like observing, perceiving and understanding causal relations, the forming of gestalts, doing prequantitative experiments, and finding concepts and empirical laws between them as parts of the pupils’ external representations. Without this enlargement the findings would have been much more weaker and given in some ways the wrong picture of learning in a small group. For example, alongside the theoretical incorrect fragment of the electric current *Electrical current moves quickly to light the bulbs simultaneously (2)*, there also existed an observation-based fragment *Brightness as a property of the bulb (4)*, and a prequantitative fragment *Brightness of bulbs as a measure of the electric current (7)*. These examples clearly show the advantage of also including the empirical aspects of learning in the representing process. The findings also show that the uncovered underdevelopment of theoretical explanations seemed not to harm the small group’s learning. On the other hand the emphasis on empirical conceptualisation is in line with FRAME, which focuses on qualitative understanding of DC-circuit phenomena. A capability for interpreting observations, making conclusions and comparing observed phenomena belong to this kind of qualitative understanding. (FRAME 2004)

The study confirms earlier reports of a small group’s positive influence on learning (see section 4.3.2). According to this study, the pupil’s own talk and thinking aloud seem to promote learning in a teacher-guided learning environment. The small group of third-graders learnt to do experiments and to make hypotheses about phenomena very well. The experiments or concepts to be learnt did not seem to be too difficult for nine-year-olds, as the small group functioned actively and keenly all the time. In this respect, the answer to the scientific starting point “How to guide pupils to learn DC-circuit phenomena” (see

section 1.2.1), is to use a teacher-guided discussing small group learning environment, where learning is promoted by supporting the pupil's own empirical operations and modelling, and which has used historical modelling of DC-circuit phenomena as source of innovation.

## 9.5 Implications for further research

This study, *A Historical Approach to Children's Physics Education: Modelling of DC-circuit phenomena in a Small Group*, is a multidimensional design research. It includes aspects of Experimental-centred representation, small group learning, children's learning and modelling of DC-circuit phenomena, and using the historical models as a source of innovation for teaching. Thus there are lots of different possibilities for further research.

The Experimental-centred representation –approach is a new approach, which offers a strong analysis tool – the framework of model – to the pupils' learning process. The value of the framework of model in learning electricity is particularly the transparency of the different steps of learning: the fragments of pupil's external representation clearly show what the pupil already understands and what is yet difficult. So, it would be essential to try to track the pupil's learning process in longer-term studies, for example during the classes of comprehensive school. The analysis tool could also be applied in different subject areas in natural sciences. It would also be very valuable to know if it is possible to apply this kind of analysis tool to the learning process of a whole class.

Using small group learning showed to be a good choice. Its success was partially dependent on the presence and guiding of the teacher, but the small group itself seemed to be a pupil-activating learning environment as well. The pupils clearly enjoyed talking about the subject matter and learning together. Designing other small group learning techniques or tools, which activate learning and are suitable for whole class would be more than desirable. In this study the designed connection cards are a good example of a pupil-activating learning tool, which can be used in small groups. In this study connection cards proved to be an effective tool in simulating real connections of DC-circuits. The use of the connection cards in a classroom situation with several small groups should be studied. An essential question is, how to collect and easily utilise pupils' talk with connection cards in several simultaneous small groups. Different ways of using the cards would also be worth researching. It would be also possible to design similar cards to other subject areas, for instance magnetism.

The use of the development of historical models of DC-circuit phenomena as a starting point of the design research encouraged highlighting the phases of qualitative concept formation. The concept formation processes of DC-circuit phenomena, which were behind the historical models, are excellent examples of the impact of prequantitative experiments and modelling in concept formation. There seems not to be need for special measuring equipment in the qualitative stage of conceptualisation, but the qualitative identifications, classifications and comparisons can be the centre of attraction. The historical modelling processes of DC-circuit phenomena also uncovered the meaning of language and discussion in concept formation. In Volta's and Galvani's debate during the modelling

process of DC-circuit phenomena the language of written articles showed the development of historical models. Thus, in addition to historical models and the experimentality behind them, also the meticulousness in qualitative concept formation and meaning of language in developing the historical models are worth further research in other subject matters of physics as well.

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## Appendixes

### Appendix 1: Criteria for choosing pupils for the teaching experiment

#### Oppilaiden valinnan kriteerit opetuskokeilua varten

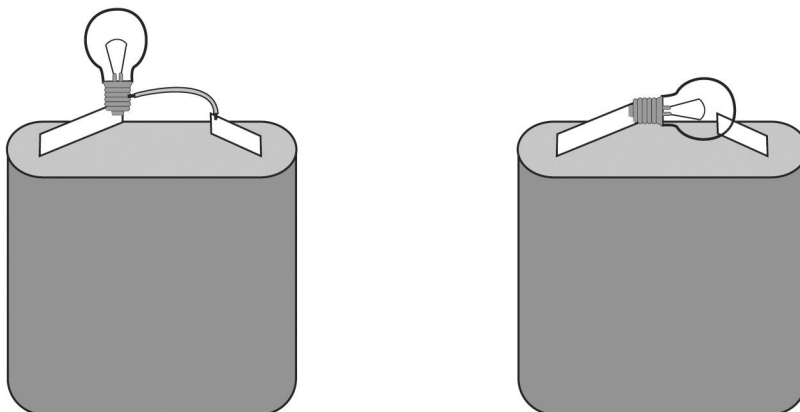
Opetuskokeiluun valitaan luokalta kaksi tyttöä ja kaksi poikaa. Oppilaat työskentelevät yhtenä ryhmänä, joten on tärkeää, että valitut henkilöt tulevat toimeen keskenään.

Opetuskokeiluun valittujen oppilaiden tulisi olla:

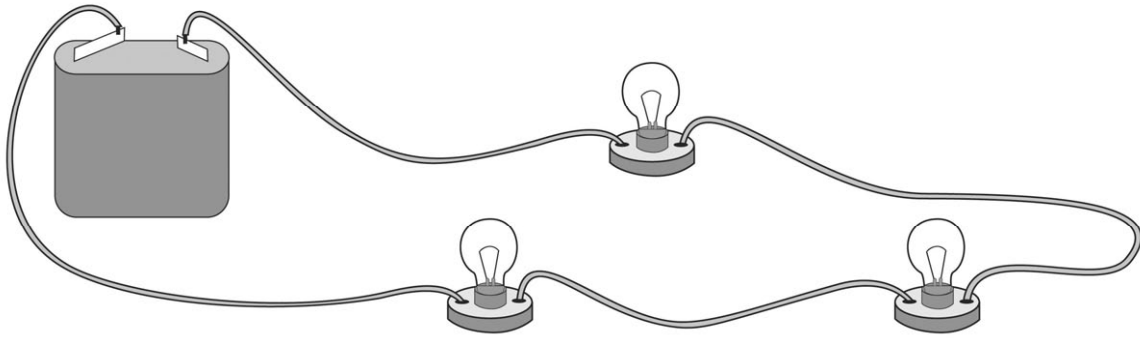
- innostuneita
- sosiaalisia
- ryhmätyöhön kykeneviä
- edustaa tiedollisesti luokan keskitasoa (ei kaikkein lahjakkaimpia, muttei myöskään heikoimpia oppilaita)
- ei liian ujo, eikä hallitseva oppilas
- tottunut ilmaisemaan asioita suullisesti ja pohtimaan opittua ääneen
- mielellään ei aiempaa osallistumista tiede-, teknologia yms. leireille, eikä alan harrastuneisuutta

Toivomme, ettei valituille oppilaille mainita etukäteen, että opetuskokeilu liittyy sähköön. Oppilaille voi esimerkiksi sanoa, että opetuskokeilu liittyy ympäristö- ja luonnontietoon.

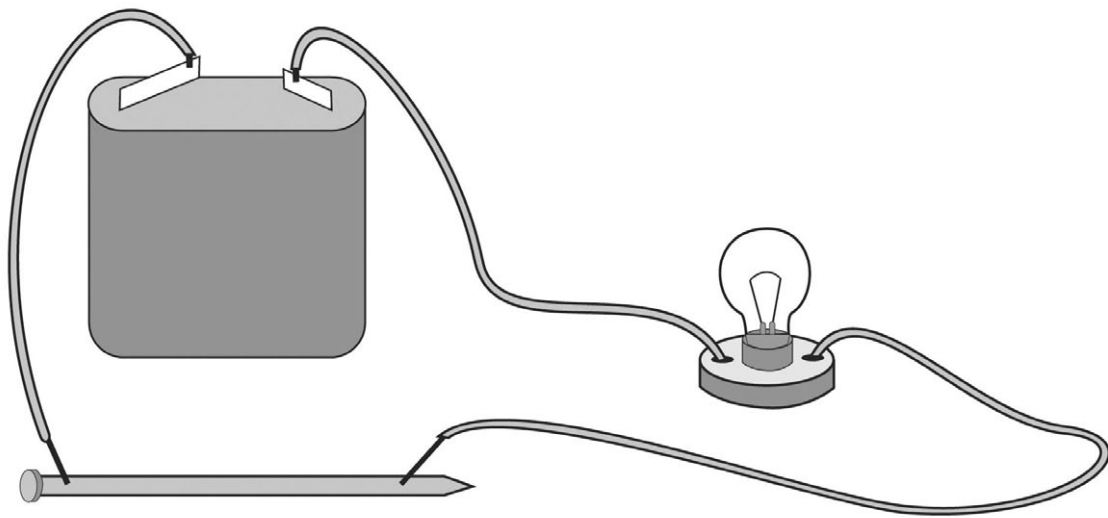
### Appendix 2: Claim cards



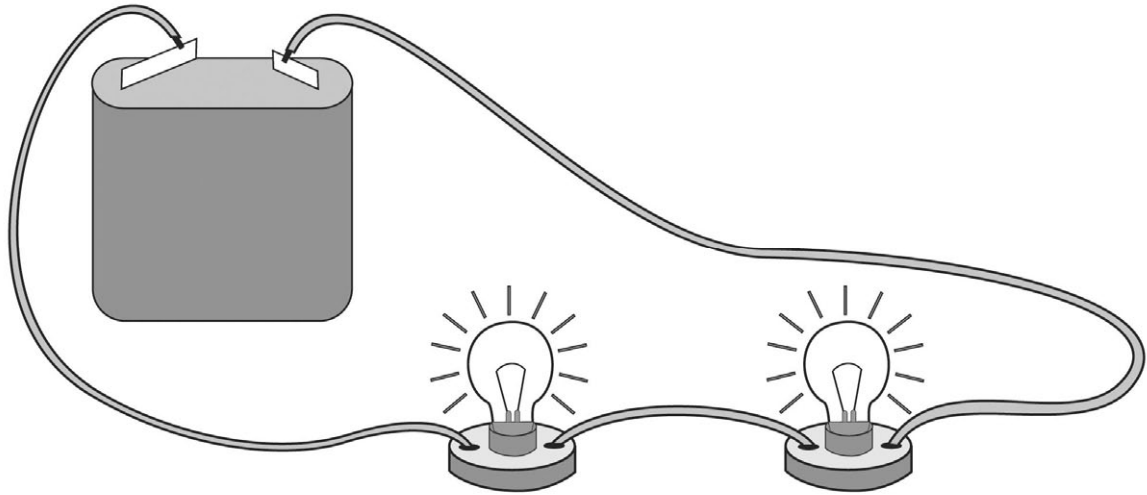
**Figure 40** *The electric circuit is closed.*



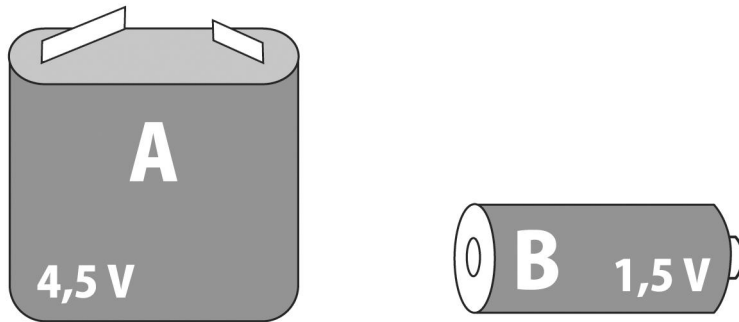
**Figure 41** *When the electric circuit is switched on, the bulb A will light first, then bulb B and finally bulb C.*



**Figure 42** *The bulb doesn't glow.*



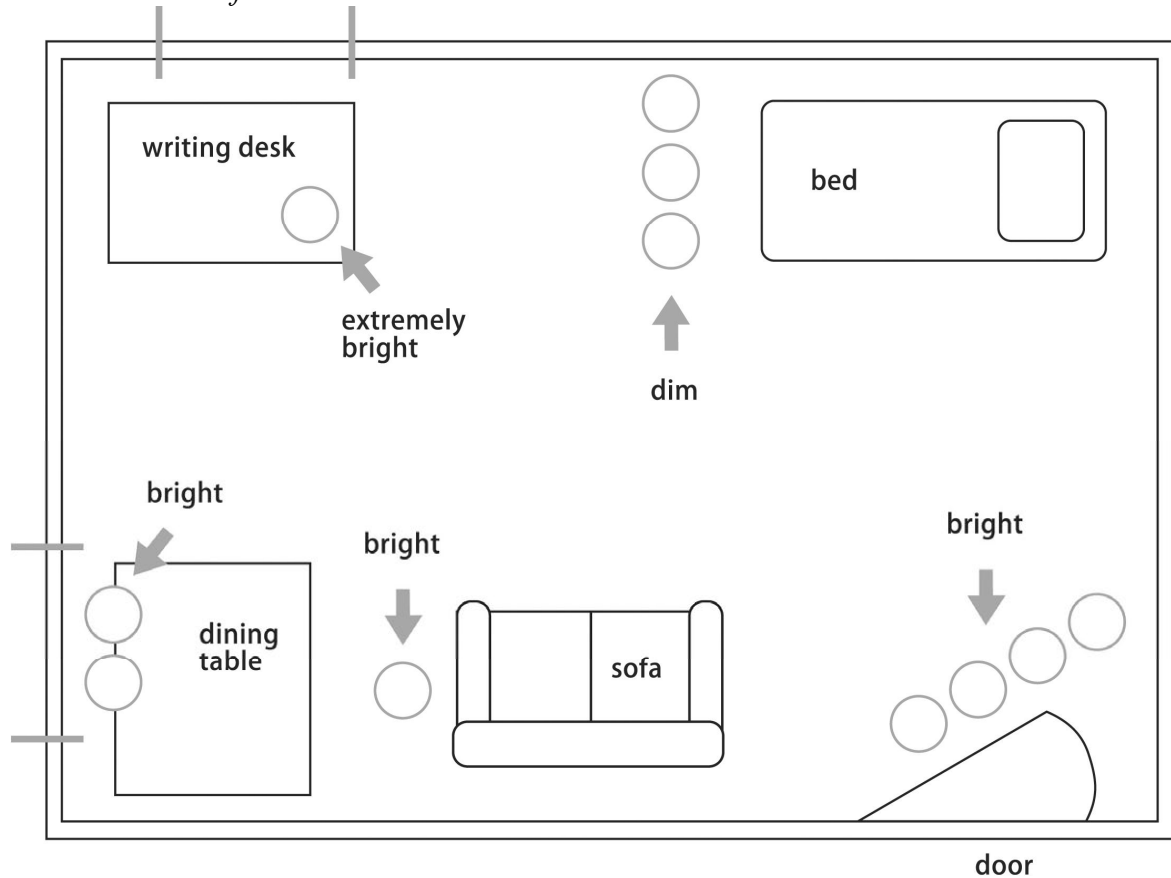
**Figure 43** *The bulbs are glowing as brightly.*



**Figure 44** *Battery A will always cause a stronger electric current in the circuit than battery B.*

### Appendix 3: Problem-tasks for the last lesson

#### *Dollhouse-electrification*



#### *Problem of a broken pocket lamp*

Suvi ja Sonja ovat etsiväkaksoset. Heidän varusteisiinsa kuuluvat mm. tarvittava määrä hyviä kirkkaasti valaisevia taskulamppuja. Joku on nyt päässyt tekemään heille kepposen ja rikkonut taskulamput. Löydätkö sinä viat? Miksi lamput eivät pala? Mitä muita vikoja lampussa voisi olla?

Ratkaise tehtävä ja laita tarvikkeet samalla tavalla kuin ne olivat aluksi. Esittele tehtävä toiselle ryhmälle ja pyydä heitä ratkaisemaan ongelmat.

## **Appendixes 4-8**

Appendixes 4-8 are in a special www-page:

<http://apumatti.helsinki.fi/lcms.php?am=18335-18335-1&preview=18335&language=1>

Appendix 4: Connecting several bulbs in series with connection cards – Constructing electric circuits of three or five bulbs

Appendix 5: Analysis leading to the fragment ”Bulbs in series light because of the electric circuit”

Appendix 6: Lighting the bulb, connections with connection cards

Appendix 7: The teacher’s guiding role

Appendix 8: Adding batteries brightens the bulb