Sci & Educ (2013) 22:1361–1387
DOI 10.1007/s11191-012-9460-x

Promoting Conceptual Development in Physics Teacher Education: Cognitive-Historical Reconstruction of Electromagnetic Induction Law

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Abstract In teaching physics, the history of physics offers fruitful starting points for designing instruction. I introduce here an approach that uses historical cognitive processes to enhance the conceptual development of pre-service physics teachers' knowledge. It applies a method called cognitive-historical approach, introduced to the cognitive sciences by Nersessian (Cognitive Models of Science. University of Minnesota Press, Minneapolis, pp. 3–45, 1992). The approach combines the analyses of actual scientific practices in the history of science with the analytical tools and theories of contemporary cognitive sciences in order to produce knowledge of how conceptual structures are constructed and changed in science. Hence, the cognitive-historical analysis indirectly produces knowledge about the human cognition. Here, a way to use the cognitive-historical approach for didactical purposes is introduced. In this application, the cognitive processes in the history of physics are combined with current physics knowledge in order to create a cognitive-historical reconstruction of a certain quantity or law for the needs of physics teacher education. A principal aim of developing the approach has been that pre-service physics teachers must know how the physical concepts and laws are or can be formed and justified. As a practical example of the developed approach, a cognitive-historical reconstruction of the electromagnetic induction law was produced. For evaluating the uses of the cognitive-historical reconstruction, a teaching sequence for pre-service physics teachers was conducted. The initial and final reports of twenty-four students were analyzed through a qualitative categorization of students' justifications of knowledge. The results show a conceptual development in the students' explanations and justifications of how the electromagnetic induction law can be formed.

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1 Introduction

Learning conceptual knowledge and scientific concepts is often examined from the perspective of conceptual change or development and has proved fruitful in guiding several aspects of research in the learning and instruction of science (Duit and Treagust 2003). In broad terms, conceptual change means that students' understanding of the concepts and conceptual system in a specific subject-matter area changes during the learning process. The change itself can be gradual or more abrupt, but it affects larger conceptual structures of the learner (diSessa and Sherin 1998; Thagard 1992). Nersessian (1992, 2008) examined the conceptual change that occurs in the process of creating scientific concepts using cognitive-historical analysis. She demonstrated how, through the closely associated use of analogies, visual representations, and thought experiments (first with experimental investigations and then with mathematical analyses), has led to conceptual change, particularly in the cases of Faraday's and Maxwell's practices (Nersessian 1984, 1992, 2008). These conceptual changes in science could also offer some insight for contemporary science instruction.

A number of studies in the area of physics education have shown that students' learning processes of scientific concepts parallel the historical developments of the same concepts. Therefore, researchers and educators have drawn inspiration from the history of physics when addressing the alternative conceptions of students, designing history-based experiments, or teaching the various aspects of physics as a science (Seroglou and Koumaras 2001). The historical events in the development of physics used, as such, in physics education, serve as a means for teaching about the process of creating scientific knowledge, such as the nonlinear development of physical theories (Stuewer 1998) or the role of chance in the progress of physics (Kipnis 2005). They can be also used for understanding the methodology of physics (Seroglou and Koumaras 2001). However, when the history of physics is used in teaching the content knowledge of physics, there are restrictions: although there are similarities between the reasoning processes of students and physicists in the history (e.g., Pocovi and Finlay 2002), there are also fundamental differences.

Seroglou and Koumaras (2001) referenced and discussed the issues of paralleling the exploration of scientists in history and students' learning. According to Seroglou and Koumaras (2001), the contemporary world of students and the past world of scientists are very different, so their experiences in these worlds are not parallel. The scientists are experts and they have deeper metacognitive understanding of their objectives and means, whereas students are the novice learners and lack the same metacognitive awareness (Seroglou and Koumaras 2001). In addition, the concepts used in history can possess different meanings or interpretations in contemporary physics or education (Seroglou and Koumaras 2001). This means that the history of physics cannot be replicated in teaching, as such; instead, the historical cases have to be modified to correspond with the needs of contemporary education.

Here, an approach is introduced, which uses historical cognitive processes to enhance the conceptual development of pre-service physics teachers' knowledge. According to Shulman (1986), "the teacher need not only understand that something is so; the teacher must further understand why it is so" (p. 9). This means that teachers should know how the knowledge is, or can be, formed. The suggested approach aims to reach this goal.

In order to contextualize the approach, the formation of the electromagnetic induction law was chosen as the topic of examination. One reason for this is that it offers rich physics content knowledge, while pertinent historical cognitive processes involved in its creation are analyzed and described by historians, philosophers of science, and cognitive scientists

(Darrigol 2000; Gooding 2006; Nersessian 1992; Tweney 2009). It is also a challenging topic for students (Chabay and Sherwood 2006; Guisasola et al. 2011; Thong and Gunstone 2008). Guisasola et al. (2011) have examined university students' understanding of the electromagnetic induction on both the macroscopic and microscopic level. They suggest that there is a need for designing and implementing didactic materials that enhance students' understanding of electromagnetic induction.

In this study, the target group of learners is pre-service physics teachers in a real teaching sequence. Pre-service physics teachers are students majoring in science or mathematics who are pursuing qualification to become physics teachers at the secondary education level. These students are enrolled in a Master's degree program in science (300 ECTS) and about half of the program consists of major subject studies. The program curriculum also includes minor subjects, which is the second subject students will eventually teach in schools (60 ECTS), and the "Pedagogical Studies of Subject Teachers" course (60 ECTS), which includes pedagogy, didactics, and a teacher practicum.

This study complements a previous study addressing a learning tool called "Didactical Reconstruction of Processes" (DRP) (Mäntylä 2011). Here, the focus is on designing and evaluating the content of teaching electromagnetic induction law.

2 Cognitive-Historical Approach and Its Application in Science Education

Nersessian's (1992) cognitive-historical approach combines the analyses of actual scientific practices in the history of science with the analytical tools and theories of contemporary cognitive sciences in order to "create a new, comprehensive theory of how conceptual structures are constructed and changed in science" (p. 5). Hence, cognitive-historical analysis considers the conceptual change from the perspective of how the scientific concepts were originally created. According to Nersessian (1992), the value of the cognitive-historical approach for physics education is that "the historical processes provide a model for the learning activity itself" (p. 40). It means that the history of physics serves as a source of designing how to construct, change, or communicate scientific knowledge in teaching. This is in line with what was discussed above; the historical processes are not replicated; they are applied for the purposes of contemporary physics education, taking into account the needs of the target student population. Carey (2009) also discusses that cognitive-historical analysis is capable of capturing many important features of human cognition related to learning.

Previous experiences from using the cognitive-historical approach in guiding the planning of didactical approaches are promising. The approach has been applied in designing curricula and teaching solutions, the results of which seem to promote and support conceptual change (see Carey 2009 and references, therein). Hadzidaki (2008) also used the cognitive-historical approach to design and propose instructional tools for promoting conceptual change while learning quantum mechanics. Hadzidaki (2008) reconstructed scientists' thought experimentation used in the birth process of quantum mechanics. In science education literature, the cognitive-historical approach has been taken into account (Seroglou and Koumaras 2001; Oh and Oh 2011; Strömdahl 2012); however, there remains a lack of explicit practical applications for the cognitive-historical approach in science education.

The cognitive-historical approach is used in this study so that the cognitive processes in the history of physics are combined with current physics knowledge in order to create the cognitive-historical reconstructions (Fig. 1). The historical models and cognitive processes mean the essential reasoning, modeling, and experiments that have led to the creation of

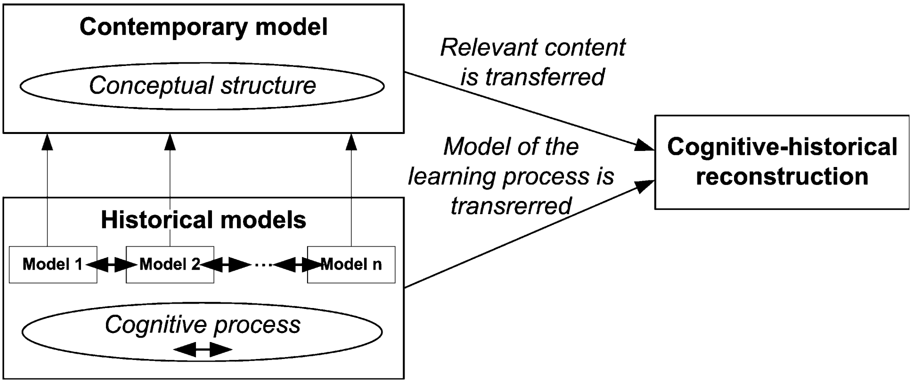

Fig. 1 Schematic representation of the forming of cognitive-historical reconstruction

new scientific concepts or ideas. Existing analyses and research literature have been used as a source of historical cognitive processes and models. Then, the creation process of a concept is adapted to its contemporary model. The emphasis of adaptation is on the relevant content for pre-service physics teachers, which means that the aspect of concept formation guides the adaptation.

3 Cognitive-Historical Reconstruction of the Electromagnetic Induction Law to Design the Teaching Sequence

The emphasis in designing the cognitive-historical reconstruction was on the process of forming the induction law because it is desirable that future teachers know how the induction law can be formed. The cognitive-historical reconstruction of electromagnetic induction is next discussed (Sect. 3.1) at the level of knowledge, which corresponds with the level at which the induction is discussed in Finnish upper secondary schools. For didactical reasons, the designed cognitive-historical reconstruction is presented in a flow chart (Fig. 2) and the steps involved in it are described in more detail in what follows. The steps of reconstruction are based on the generative use of experiments (Koponen and Mäntylä 2006) and models (Koponen 2007), which emphasizes the experiments' role in knowledge formation and justification and models' role in mediating between experiments and theory. The flow chart, as a learning tool, is discussed in more detail in the previous study (Mäntylä 2011). Finally, in Sect. 3.2, the designed cognitive-historical reconstruction is compared to the historical processes involved in the formation of electromagnetic induction law.

3.1 Cognitive-Historical Reconstruction of the Electromagnetic Induction Law for Teaching Purposes

The steps of reconstruction (referring to the numbers in Fig. 2) are:

1. *Observation and identification of phenomenon.* The starting point for exploring induction is knowledge that magnetism can be produced through electricity (Ampère's law). So, is the opposite phenomenon possible? Induction current is observed when, for example, a bar magnet is moved near a secondary coil. The observed phenomenon—the production of electric current in the secondary coil when a

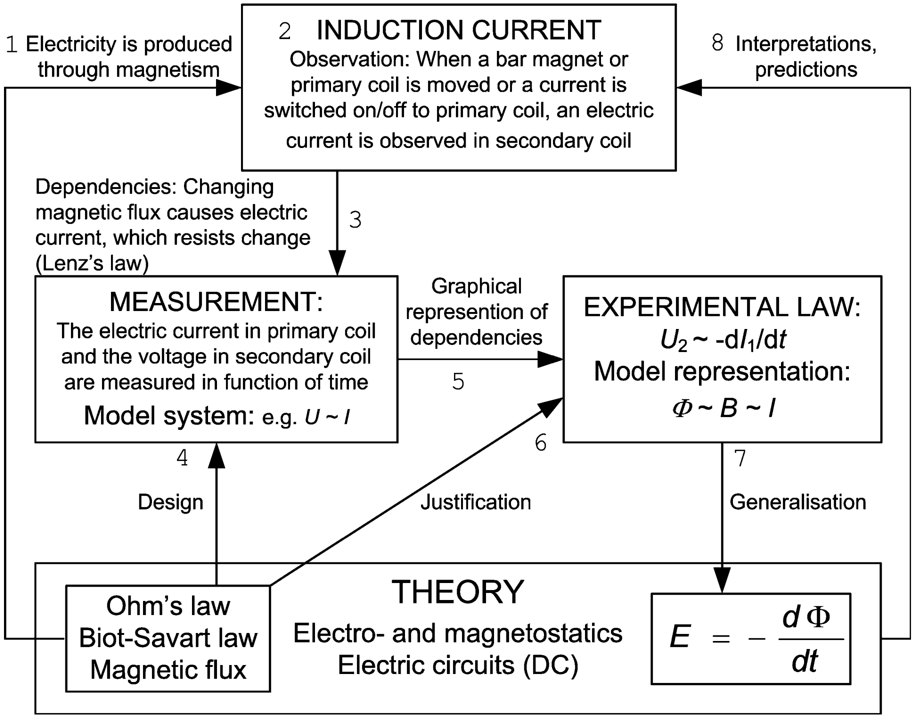

Fig. 2 Cognitive-historical reconstruction of the electromagnetic induction law

magnetic object is moved near it—is identified based on the existing theory of electro- and magnetostatics. A new feature in the phenomenon, absent from existing theory, is that electricity is produced through magnetism.

2. *Qualitative experimentation of induction current.* A bar magnet or a primary coil (connected to a battery) is moved near the secondary coil (connected to an ammeter) and the changes in magnitude and direction of induction current are observed. The bar magnet or the primary coil can be moved directly or placed at various angles toward the secondary coil's end. It is also possible to move the secondary coil near the bar magnet or primary coil and observe current changes. The experiment can be done by switching the electric current in the primary coil on and off. In addition, the angle of the coils' ends can be varied. In this experiment, the primary and secondary coils are stationary, but in the moments of switching the electric current of the primary coil on and off, induction current is observed in the secondary coil. This last experiment shows that the motion of magnetic objects is not essential; instead, the varying magnetic field experienced by the secondary coil is essential.
3. *Qualitative dependency: A changing magnetic flux through a coil.* The common changing property in the qualitative experiments is changing magnetic flux through a secondary coil. A geometrical model for understanding this is the magnetic field line model. The quantity that describes the number of field lines crossing a certain surface is called magnetic flux. For instance, when the bar magnet (fixed magnetic field) is moved near the secondary coil, the number of field lines crossing through the secondary coil changes. When the angle from where the bar magnet approaches the secondary coil's end

is altered, different numbers of field lines cross the secondary coil because the area that the field lines are crossing is smaller. The change of magnetic flux through secondary coil causes an electric current that resists the change (Lenz's law.) This qualitative dependence forms the basis for designing the quantitative experiment.

4. *Model for measurement system and measurement.* In designing the quantitative experiments, the knowledge of how to measure electric current and voltage, and how to measure results, is needed.[1] Based on qualitative experiments and the model for measurements, it is possible to design a quantitative measurement system. It consists of two coils, and the electric current in the primary coil and induced voltage in the secondary coil is measured as a function of time.
5. *Representation of measurement results.* The results of experiments are represented graphically and algebraically. From the graphs, it is observed that voltage correlates linearly with the time derivative of the electric current.
6. *Experimental law of induction and model for representation of results.* Now we have a new experimental law: $U_2 \sim -\mathrm{d}I_1/\mathrm{d}t$, which applies to the described system. Next, we examine and interpret the result in light of earlier knowledge and try to represent it in a more general way. Based on the interpretations of observations in qualitative experiments, it is assumed that the cause of measured induction voltage is the changing magnetic flux produced by the changing current of primary coil. It is then reasoned that electric current and magnetic flux are correlated. Based on Biot's and Savart's law of magnetostatics, it is expected that $B \sim I$, and the definition of the law of magnetic flux gives us $\Phi \sim B$ when a magnetic field passes through a certain surface.[2] The induced voltage measured by voltmeter is interpreted as a voltage-like electromotive force, E, which drives the current in the secondary coil.[3]
7. *Extension of theory.* The new tentative law is now in form $E = -d\Phi/dt$, which is known as Faraday's induction law.
8. *Interpretations and predictions.* The law is tested. How well does it explain the induction current phenomenon? Is it possible to make predictions about different situations, such as with coils with different cross-sectional areas and number of turns? Is it possible to explain other phenomena (e.g., eddy currents, Arago's effect, self-induction, or a rod sliding on conducting rails in a uniform magnetic field)?

3.2 Comparison of Cognitive-Historical Reconstruction for Teaching Purposes and Historical Processes in the Case of the Electromagnetic Induction Law

The reconstruction uses similar reasoning patterns and experiments to Faraday (2005/1839), but they are adapted for contemporary physics teacher education.

The starting point (Step 1 above)—examining whether electricity is produced through magnetism—resembles Faraday's motivation (following Davy's ideas) of looking for "the inductive effect of electric currents" (Faraday 2005/1839, First Series #4). It was already

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[1] For instance, keeping the voltmeter and its leads parallel with the direction of changing magnetic field (Reif 1982).

[2] In upper secondary schools, the experimental Biot-Savart law, not the Ampère-Laplace law or Ampère's circuital law, is discussed, and occasionally the equation for magnetic flux density for solenoids, where $B \sim I$, is given. The algebraic definition given to magnetic flux at upper secondary school level is $\Phi = BA$.

[3] Here the role of electromotive force is understood in the same way as in the study of Thong and Gunstone (2008, pp. 34–35); an elaborate account of the relationship between electromotive force and voltage is discussed, for example, in an article by Varney and Fisher (1980).

known that magnetism can be produced through electricity; Faraday began to investigate the presumed inverse phenomenon. The same motivation applies perfectly in contemporary teaching because the electro- and magnetostatics are discussed before moving on to electromagnetic induction.

The qualitative experiments (described in step 2) parallel Faraday's experiments (Darrigol 2000). The qualitative experiments are used for experimental reasoning similarly to how Faraday used them. Although the experimental set-up uses contemporary devices, it resembles Faraday's experiments with early coils and Volta's piles. The first two experiments (moving the bar magnet or the primary coil near the secondary coil, with their variations) are commonly used in teaching electromagnetic induction, but the third one (switching current on and off in the primary coil) completes the set of qualitative exploration of induction currents. It also highlights the transient nature of the induction phenomena. It was a surprise to Faraday (Darrigol 2000) and it is the first time in upper secondary school physics when a teacher is expected to discuss this type of transient dependence, explicitly.[4]

In step 3 above, the lines of force are used in order to explain the induction phenomena, qualitatively; this has similarities to Faraday's explanation. However, in the reconstruction, the lines of force are discussed in the current meaning as geometrical and visual representations of the field, contrary to Faraday, who used the lines of force in ambiguous ways (i.e., as convenient representation tools and also as physical entities) (Darrigol 2000; Nersessian 1985; Pocovi and Finlay 2002). In the first sense, Faraday used lines of force to describe both the geometry of the field and the strength of it. In the reconstruction, the lines of force are related to magnetic flux (compared with Gooding 2006), one of the three quantities describing the strength of the magnetic field. One purpose behind this is to motivate the appearance of magnetic flux in the electromagnetic induction law. Connecting magnetic flux to field lines gives a physical meaning for this quantity. Lenz's law is also inferred from the experiments.[5]

In steps 4–6, the quantitative experiment is designed on the basis of the third qualitative experiment, and a microcomputer-based laboratory is used for the measurements. Based on the measurement results, the experimental induction law is established in mathematical form. This differs from Faraday's method because Faraday did not use mathematical formulation (Darrigol 2000; Tweney 2009). However, the role of experiments in the reconstruction resembles Faraday's way of using experiments in the role of generating new knowledge.

In step 7, the electromagnetic induction law is presented in one of its current mathematical formulations. Faraday published the original establishment of induction law in 1832. Twenty years later, he designed an apparatus for quantitatively measuring this, such that "the sum of power contained in any one section of a given portion of [magnetic] lines is exactly equal to the sum of power in any other section of the same lines…" (qtd. in Gooding 2006, p. 54, 57). He expressed this quantitative law visually in 1852 (Gooding 2006, p. 54, 57).

Finally, in step 8, the law is tested in different situations. For example, it is applied to explain Arago's effect. In the history of physics, Arago's effect preceded Faraday's induction experiments; however, the phenomenon remained unexplained until Faraday conducted a series of experiments in order to explain the effect (Darrigol 2000).

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[4] Actually, in Newton's second law, the relation of force to time derivative of momentum could be the first transient relation, but, usually, it is bypassed in upper secondary school physics.

[5] Faraday first gave a rule for determining the direction of induced currents, but Lenz formed a more general rule for this determination.

In the cognitive-historical reconstruction, the knowledge is justified in similar ways: through experiments and bi-directional reasoning between experiments and theory. This type of justification is called generative justification of knowledge (Koponen and Mäntylä 2006; Nickles 1993). Faraday's style of experimentation is an example of the generative use of experiments, which later affected, for example, the practices of Helmholtz and Hertz (Koponen and Mäntylä 2006). Hence, the historical way of justifying knowledge is preserved in the reconstruction.

In some teaching approaches, electromagnetic induction instruction starts with introducing Arago's effect or jumping or moving an aluminum ring. In the reconstruction, electromagnetic induction law was approached using qualitative experiments similar to Faraday's experiments because they offer a perceptual and understandable starting point for learning electromagnetic induction. Arago's effect and jumping aluminum rings are intriguing experiments, but students do not generally possess the means to reason through the cause of the observed phenomena.

Often, teaching electromagnetic induction starts with the motional electromagnetic induction law of the conductor in a uniform magnetic field, based on the Lorentz force and the electromagnetic induction law derived from it. Here, the formation of the induction law is based on the experiments resembling the historical experiments exploring induction. The approach chosen here is perhaps not the simplest one, but it highlights the independent nature of the law, not just presenting it as a subordinate to the Lorentz force. Also, historically, the induction law was constructed first on a macroscopic level; later, through the work of Lorentz, the microscopic reasoning of electromagnetic induction became possible (Nersessian 1984). Of course, a full understanding of induction phenomena also requires examination at a microscopic level as it is discussed by Guisasola et al. (2011), but this can be done in instruction afterwards (for instance, in step 8 of testing the induction law).

4 Evaluation of the Cognitive-Historical Reconstruction of Electromagnetic Induction Law in Instruction

In order to evaluate the uses of cognitive-historical reconstruction in instruction in the case of electromagnetic induction law, students' reports about the formation of electromagnetic induction law were analyzed. Students produced reports before (initial reports) and after (final reports) the teaching sequence. The following research questions were formulated:

1. What kinds of experiments and models did students' reports contain, initially and finally?
2. How were experiments and models in students' reports used to explain the formation of induction law, initially and finally?
3. How was the formation of electromagnetic induction law in students' reports justified, initially and finally?

In the previous study (Mäntylä 2011), the effect of the graphical learning tool for learning, DRP (the flow chart with its steps in Fig. 2 without the content related to electromagnetic induction), was evaluated. In this study, the focus was on the effect of the cognitive-historical reconstruction (introduced in previous section) to the students' descriptions of how electromagnetic induction law can be formed. There is some overlap between the studies because they are parts of the same larger entirety. As stated in the first study, "The DRP [learning tool] is simultaneously a tool for teaching, learning and evaluating" (Mäntylä 2011, p. 8). This means that the tool guided the formation of the cognitive-historical reconstruction introduced above, and it directed students' attention to certain aspects of knowledge formation. The first research question helps to evaluate the changes in the use of specific experiments and models. The second research question allows probing the changes in the purposes and use of experiments and models in the process of forming the electromagnetic induction law. The third question helps to evaluate the effect of cognitive-historical reconstruction for conceptual development, at large.

4.1 Teaching Sequence and Research Participants

The study was conducted in autumn 2005 in an advanced-level course of pre-service physics teachers called "Conceptual Foundations of Physics" (5 ECTS). The duration of the course was 7 weeks and was held at the beginning of the autumn semester. Altogether, 28 students attended the course, nine of whom were physics majors, and nineteen were physics minors. The reports of 24 students are examined here. Four students neither participated in the exercises, nor returned the initial report, so their reports are excluded from the data. The physics minor students had mathematics as their major subject, except one who was a pharmacist pursuing another degree. The students were primarily third or fourth year students, nine were female, and fifteen were male. The physics majors had studied the calculus-based introductory and intermediate-level physics courses (70 ECTS) and the physics minors had studied the introductory physics courses (25 ECTS). They all had attended the introductory course on electromagnetism, so all students had studied electromagnetic induction prior to this teaching sequence.

Before the teaching sequence on electromagnetic induction, the aspects of experiments' and models' role in physics concept formation (for details, see Koponen and Mäntylä 2006; Koponen 2007) were discussed during course lectures; also, the graphical learning tool, DRP, was introduced in the lecture. In the teaching sequence, first students were asked to produce initial reports including flow charts and essays clarifying the formation of the electromagnetic induction law, based on experiments and theory. In more detail, the task for the pre-service teachers (see Appendix 1) was to represent how the identification and interpretation of induction phenomena, and the design of experiments, are based on known theories of electro- and magnetostatics. In addition, they had to think about what kind of models would be needed to interpret the experimental results and how the induction law is incorporated as a part of the theory of electrodynamics. This was asked to present at the knowledge level of upper secondary school physics students; the idea was to think about how, based on information that had been covered in the upper secondary school up to that point (direct current circuits, electrostatics, and magnetostatics), the electromagnetic induction law could be formed. The pre-service teachers had to apply knowledge they already possessed. They were encouraged to use textbooks and other available material while completing the task.

Second, students participated in the exercises (two sessions, 90 min each) in which the electromagnetic induction law was discussed in small groups. The instructor followed groups as they worked and guided individual groups through conversational questions. Groups' ideas were compared at the end of the exercises during an instructor-led joint discussion. During the exercises, the cognitive-historical reconstruction of electromagnetic induction law was not taught; instead; students' ideas were further developed through conversational questions: Where did you develop the reason to begin exploring induction phenomena? What can you infer from this qualitative experiment? Does this one experiment provide enough information on induction phenomena, or would it be useful to do other experiments, as well? Given that this is your quantitative experiment, how does it follow from qualitative experimentation? What kind of knowledge of physics is needed in order to design this experiment? Through these types of questions, the role of specific experiments and models—and how they create a chain of reasoning in order to form the electromagnetic induction law—were discussed during instruction. In addition, the experiments were not conducted, but the ideas and practical realizations of the experiments were discussed. After the exercises, students individually produced final reports, including flow charts.

4.2 Data and Data Analysis

The research data consists of 24 initial and 24 final reports, each of which included a flow chart and an essay providing further explanation of the flow chart. The nine physics majors were interviewed twice. Pre-interviews were held to discuss their initial reports before the teaching sequence and post-interviews were held to discuss their final reports about 3 months after the completion of the final reports. Appendix 2 provides an example of an initial report and Appendix 3 shows an example of final report. The content and coherence in students' reports were qualitatively analyzed and categorized. In practice, the reports were read through several times, essential features were marked, and keywords and descriptions were written down. Then, by comparing the similarities and differences between the specific features, key words, and descriptions of reports, the final categories were established.

In analyzing the contents of the reports, attention was paid to the use of certain essential content elements: the experiments and models. Different possibilities exist for approaching or classifying results, especially the models, as is discussed by Harrison and Treagust (2000), and recently by Oh and Oh (2011). The emphasis of analysis focused on the use and application of experiments and models, not, for example, on their external features (Koponen and Mäntylä 2006; Koponen 2007) because the focus was on how students use them in forming knowledge. For example, field lines are often discussed as visual representations or models; here, they are classified from the perspective of their role in the formation of knowledge; that is, whether they were used for describing some features of the phenomenon or for reasoning about the phenomenon (compare with Gooding 2006 or Nersessian 1992).

Different experiments and models were first identified from the students' reports, and their frequencies in initial and final reports were documented. Second, the use of experiments and models in different stages of forming the electromagnetic induction law was examined. In this, the DRP guided the formation of different stages: the phenomenon, measurement, interpretation, extension, and their sub-stages. Third, the coherence of the content in students' reports was analyzed and categorized. The focus was on how a student argues, explains, or describes the formation of the induction law, especially how the student describes the connections between different stages in forming said law. Attention was paid to the premises a student used as a starting point in his/her explanations, to the physical correctness of argumentation, and to the logical order and rationality of the justification. In this analysis, the ways in which students used experiments and models in their reports to construct the electromagnetic induction law plays an important role. These features were then analyzed from the perspective of how the experiments and models support students' argument chains. Finally, the overall justification of knowledge was analyzed based on the evident categories: inductive (emphasis on experiments), consequential (emphasis on theory), or generative justification of knowledge (both experiments and theory are needed) (see Koponen and Mäntylä 2006 for more details).

In the previous study (Mäntylä 2011), only the reports of physics majors were analyzed; thus, only nine initial and nine final reports were covered. In the earlier study, the use of experiments and models in different stages was also analyzed; in this study, they were analyzed in more detail and more deeply (sub-stages are included), because, in this case, the use of content knowledge was of special interest. The more detailed analysis led to few differences in categorization between studies. For instance, in the previous study, if the student described the experiment of the rod sliding on the conducting rails in uniform magnetic field, it was mainly categorized as a descriptive model, because its practical implementation was not described. In this re-analysis, it was decided to categorize it as a quantitative experiment, despite the deficiencies of descriptions. The coherence of content was analyzed similarly to the previous study. In the current study, the analyzed data was more extensive than in the previous study; the initial and final reports of all 24 students were covered. In addition, the analysis of the different experiments and models in the reports, and the categorization of overall knowledge justification, is novel compared to the previous study.

In the interviews, the physics majors were asked to explain their flow charts. In addition, in the final interviews, students also compared their initial and final flow charts. These transcribed interviews were used for confirming the categorizations of reports. First, the roles of experiments and models were analyzed and categorized using similar methods of analysis to those used in the case of the reports. Second, overall coherence and knowledge justification were categorized from students' explanations during the interviews. Finally, the categorizations of reports and interviews were compared, the results of which showed that the categorizations were convergent. The interview sample covers only 38 % of students' reports and only the physics majors. However, because the categorizations were convergent, it is assumed that the analysis of the physics minors' reports is also trustworthy. Appendix 4 shows the categorizations of example reports (Appendices 2, 3), which are given to illustrate the categorizations.

5 Results

The students' reports (flow charts and the essays accompanying the flow charts) were analyzed from the viewpoint of the content and its overall coherence. During the course, the role of experiments and models in concept formation were discussed (Koponen and Mäntylä 2006); therefore, it is expected that students' reports will include how experiments are applied in supporting knowledge formation and how models are applied in designing and interpreting the experiments. In the categorization of experiments and models, the emphasis was on their use and application. The categories and their descriptions are presented in Table 1. The contents of the reports are categorized due to these categories of experiments and models in what follows. In Tables 2, 3, 4, and 5 and 7, 8 and 9, all frequencies of different categories are shown in order to demonstrate the spread of, and changes in, the categories. When a category is found in every third student's report or more often, it is shown in bold.

5.1 Experiments and Models in Students' Reports

In order to construct a picture of the kind of experiments and models students use in forming the induction law, the experiments and models were identified from the reports as presented in Tables 2, 3, 4, and 5.

In Table 2, the qualitative experiments are presented. Initially, students presented one qualitative experiment, at best. The most popular was the experiment with a bar magnet

Table 1 Categories of uses of experiments and models in students' reports

Category	Description
Qualitative experiment	Perceiving regularities and changes in the phenomenon without precise measurements
Quantitative experiment	Include precise measurements
Descriptive model	The phenomenon is described using terms or causes that cannot be observed in an actual situation. An experimental situation is described so that instead of the experimental setting, the model of a situation is described
Interpretative model	In order to proceed in the formation of the induction law or in explaining observations or results, some piece of earlier, existing theory is used in a certain context in a limited way

Table 2 Qualitative experiments in students' reports

Qualitative experiment	Initial	Final
Bar magnet and coil: Moving bar magnet near or inside the coil	**50 % (12)**	**96 % (23)**
Effect of movement or the speed of movement	17 % (4)	**46 % (11)**
Direction of phenomenon	–	**33 % (8)**
Moving the coil when magnet is stationary	8 % (2)	**50 % (12)**
Effect of the magnitude of magnet or turns of coil	17 % (4)	8 % (2)
Effect of iron bar inside the coil	13 % (3)	–
Two coils: Moving primary coil, secondary coil stationary	4 % (1)	**46 % (11)**
Two coils: Changing the current/voltage in primary coil (e.g., switching the current on/off or using alternating current/voltage)	13 % (3)	**83 % (20)**
Moving secondary coil, primary coil stationary	–	17 % (4)
Effect of movement or the speed of movement	–	17 % (4)
Direction of phenomenon	–	**33 % (8)**
Effect of the magnitude of current or the turns of coils	–	25 % (6)
Effect of iron bar inside the coil	–	25 % (6)
Current loop in magnetic field of a magnet	13 % (3)	4 % (1)
Magnet on incline metal plane	4 % (1)	–
Jumping or swinging aluminum ring	4 % (1)	8 % (2)
Conducting wire as a jump-rope in Earth's magnetic field	4 % (1)	–
Delay on the lighting up of a bulb (self-induction)	4 % (1)	–

and coil (50 %). Only a few students explored the experimental situation further; a majority of students were satisfied when they presented an experiment, where induction phenomenon can be observed. There were also a few arbitrary experiments that students selected from textbooks (e.g., a conducting rod as a jump rope in Earth's magnetic field). In final reports, almost all students described the experiment of moving a bar magnet near or inside the coil (96 %). Compared with the initial report, many of them also presented further experimentation with a bar magnet and coil (e.g., effect of movement or the speed of movement (46 %) or moving the coil instead of the bar magnet (50 %)). Many students also repeated the experiment using two coils (46 %). Most students presented the experiment with two coils, altering the current in the primary coil (83 %). Some students also

Table 3 Quantitative experiments in students' reports

Quantitative experiment	Initial	Final
Two coils: The electric current in primary coil and the voltage in secondary coil are measured as a function of time	17 % (4)	**88 % (21)**
Coil in uniform magnetic field	–	8 % (2)
Current loop in (uniform) magnetic field	25 % (6)	–
Dropping bar magnet through coil or current loop	8 % (2)	–
Conducting rod sliding on conducting rails in uniform magnetic field	29 % (7)	–
Measuring inductance (self-induction)	–	4 % (1)

Table 4 Descriptive models in students' reports

Descriptive model	Initial	Final
Changing magnetic field or magnetic flux induces electric field, electric current, or voltage	**33 % (8)**	17 % (4)
Changing magnetic flux density induces electric field, electric current, or voltage	4 % (1)	4 % (1)
A current or voltage is induced in current loop or conducting wire in changing magnetic field	17 % (4)	13 % (3)
A current or voltage is induced in current loop or conducting wire when it moves in (uniform) magnetic field	8 % (2)	4 % (1)
The induced voltage is a consequence of the effect of the magnetic field to the moving charged particle	4 % (1)	–
The electric current does come from nothing	8 % (2)	–
Conducting rod sliding on conducting rails in uniform magnetic field as a thought experiment	8 % (2)	–
The Lorentz force as a force acting on a moving charged particle	4 % (1)	4 % (1)
The field lines as a descriptive model	–	4 % (1)
Maxwell's equations as extension of theory	25 % (6)	8 % (2)
Accelerating charge carriers explained by the new law	4 % (1)	4 % (1)
The relativity principle connects the induction law to the other laws of electromagnetism	4 % (1)	–

described further variation of these experiments with two coils, such as observing the direction of the phenomenon (33 %). Therefore, in the final reports, there is evidence of more versatile experimentation with the same set-up of equipment, and they form a connected whole of exploration of the induction phenomenon.

As can be seen in Table 3, there are different quantitative experiments presented in initial reports, such as the traditional experiment with the rod sliding on conducting rails in a uniform magnetic field (29 %), or an experiment in which a current loop is moved or rotated in a (uniform) magnetic field, or the field is changed and the loop is stationary (25 %). However, most of these experiments where inadequately described, or their descriptions where quite idealized or impractical (e.g., the ammeter is connected to the ends of a current loop). In a few cases, there were clear misconceptions relating to the induction (e.g., the current loop was pulled into uniform field or the obtained relation from the experiment was that the induced voltage is proportional to the magnetic flux).

Table 5 Interpretative models in students' reports

Interpretative models	Initial	Final
The voltage/current is induced without a voltage/current source in a circuit	4 % (1)	**46 % (11)**
It is known that current produces magnetism (Ampère's law), is it possible to produce current through magnetism?	8 % (2)	17 % (4)
Field lines in explaining the occurrence of induction phenomena	–	13 % (3)
Induction phenomena occurs only when magnetic field or magnetic flux changes based on qualitative experiments	–	25 % (6)
Direction of induced current (Lenz's law)	4 % (1)	25 % (6)
Applying existing knowledge (e.g., of direct current circuits) in designing the measurement system	–	**50 % (12)**
Experiment or model of conducting rod sliding on conducting rails in uniform magnetic field		
Deriving motional emf from Lorentz force	8 % (2)	–
Deriving Faraday's induction law from motional emf of moving conductor	25 % (6)	–
Interpreting the experimental law of experiment with two coils based on existing knowledge		
$\Phi = BA$ or Gauss's law	–	**50 % (12)**
Biot-Savart law or Ampère's law	–	**79 % (19)**
Generalization of results: Faraday's induction law as a basic experimental law of electrodynamics	17 % (4)	**38 % (9)**
From Faraday's induction law to Maxwell's 4th equation	4 % (1)	4 % (1)

In the final reports, almost all students (88 %) presented the experiment with two coils as the quantifying experiment for the induction law. The experiment to measure inductance was presented as an interpretation or prediction of the formed induction law.

Both initial and final reports included arbitrary descriptive models; however, the frequency of descriptive models decreased in final reports, as can be seen in Table 4. This is a positive development, because although the descriptive models usually contain relevant information, the way they connect to the formation of induction law remains unclear.

As can be seen in Table 5, students do not initially use models much in an interpretative way. However, most of those students who presented the (thought) experiment of a rod on conducting rails (29 % as a quantitative experiment, see Table 3; and 8 % as a descriptive model, see Table 4), also demonstrate how the induction law is derived from the experiment (25 %). Two students (8 %) also showed how the Lorentz force is applied as a starting point for an explanation of the experiment.

In the final reports, the frequency and variation of interpretative models increased. They are applied in designing the measurement system (50 %) and in deriving the general electromagnetic induction law from the experimental law by using the definition of magnetic flux (50 %) and the Biot-Savart law or Ampère's law (79 %).

5.2 Role of Experiments and Models in Students' Reports

Next, how students used experiments and models in forming the electromagnetic induction law was more closely examined. In order to do this, the process of forming the induction law was divided in different stages, which are in accordance with the learning tool (see the chart in Fig. 2 and the description of its steps without the content concerning the electromagnetic induction law). The main stages are phenomenon, measurement, interpretation, and extensions, which are presented, with their sub-stages, in Table 6.

The use or application of experiments and models in different stages is presented in Table 7. In the initial reports, most of the students described the observation of the induction phenomenon, including elements that cannot be observed in authentic situations. They used mainly descriptive models (Descriptive models, Initial, Observing, 67 %). Only 46 % of students presented a qualitative experiment for observing the induction phenomenon (Qualitative experiments, Initial, Observing). Most of the reports had some kind of quantitative experiment (Quantitative experiments, Initial, Conducting, 67 %) (compare with Table 3), but, generally, the experiment was described so that it was impossible to see how the experiment could be conducted for real or what could be inferred from the experiment. Some students presented a qualitative experiment instead of the quantitative experiment (Qualitative experiments, Initial, Conducting, 13 %) or a descriptive model (Descriptive models, Initial, Conducting, 17 %). Most of the models that students used, initially, were descriptive, which means that students presented relevant knowledge relating to the formation of electromagnetic induction law, but how exactly it was used in the formation was unclear.

In the final reports, all students presented a qualitative experiment for observing the induction phenomenon (Qualitative experiments, Final, Observing) and 71 % of them also presented a set of qualitative experiments wherein the causes of the phenomenon were explored or inferred (Qualitative experiments, Final, Decomposing). Furthermore, 33 % of students also explained how the qualitative experiments are used in designing the quantitative experiment (Qualitative experiments, Final, Designing). All students, except one, presented a quantitative experiment (Quantitative experiments, Final, Conducting, 96 %). The quality of the descriptions of the quantitative experiment also improved compared to the initial reports; they included information about how the experiment can be conducted for real and what is inferred. The use of descriptive experiments decreased, and, instead,

Table 6 Different stages of forming the electromagnetic induction law

Stage Sub-stage	Description
Phenomenon	
Identifying	How phenomenon is identified. Corresponds to step 1 in Fig. 2
Observing	How phenomenon is observed. Corresponds to step 1 in Fig. 2
Decomposing	Knowledge elements that are used when the phenomenon is decomposed, i.e., what are the causes of phenomenon and how they are inferred. Corresponds to steps 2–3 in Fig. 2
Measurement	
Designing	Knowledge elements used when designing the quantitative measurement. Corresponds to steps 3–4 in Fig. 2
Conducting	How the induction law is quantified. Corresponds to steps 4–5 in Fig. 2
Interpretation and extensions	
Interpretation	The knowledge elements used when interpreting the measurement results. Corresponds to steps 6–7 in Fig. 2
Extending and predicting	The role of the formed law in theory, predictions, or further experiments made on the basis of the formed law. Corresponds to step 8 in Fig. 2

the models' use in interpretative ways increased. This means that the models were used in mediating between experiments and theory, and that the models are better connected to the whole. A full 63 % of students used interpretative models in identifying the induction phenomenon (Interpretative models, Final, Identifying), 58 % in designing the quantitative experiment (Interpretative models, Final, Designing), and 92 % in interpreting the experimental results (Interpretative models, Final, Interpreting). Based on the increase of the frequencies of experiments and models in students' reports shown in Table 7, the students appeared to learn to use experiments and models as part of the process of forming the electromagnetic induction law.

Next, the overall use and application of the experiments and models was examined. Therefore, students' reports were classified and categorized based upon the coherence of knowledge claims using experiments and models. For the purposes of this study, coherence means that the steps between different stages represented in the flow charts and accompanying essays are well argued and justified. The categories were formed, as follows:

1. *Coherent.* The knowledge claims are coherent or almost coherent throughout the report. The order of argumentation must be logical and rational. Some ambiguities, however, are allowed.
2. *Partly coherent.* Separate stages of the report are coherent, but between separate stages, there are gaps. The argumentation and justification chains thus lack overall coherence.
3. *Incoherent.* There are several substantial gaps between different stages in the report. Gaps are so serious that, in practice, they prevent the reader from following the exposition.

An example of an incoherent flow chart and report is given in Appendix 2. In that example, the report is more like a list of relevant statements and notions, but the logical connections between the statements are ambiguous. In addition, the shifts between different stages of the flow chart are left unexplained and happen in vague ways. The argumentation lacks logical support and remains obscure.

An example of a coherent flow chart and report is given in Appendix 3. This flow chart has substantial coherence; the experiments are described in sufficient detail to understand how they work, their use in supporting concept formation is developed in clear phases, and

Table 7 Frequencies of the experiments and models in different stages of knowledge formation

	Qualitative experiments		Quantitative experiments		Descriptive models		Interpretative models	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Phenomenon								
Identifying	4 % (1)	4 % (1)	–	–	8 % (2)	–	13 % (3)	**63 % (15)**
Observing	**46 % (11)**	**100 % (24)**	–	–	**67 % (16)**	**46 % (11)**	–	–
Decomposing	4 % (1)	**71 % (17)**	–	–	8 % (2)	4 % (1)	–	**46 % (11)**
Measurement								
Designing	–	**33 % (8)**	–	–	–	4 % (1)	8 % (2)	**58 % (14)**
Conducting	13 % (3)	4 % (1)	**67 % (16)**	**96 % (23)**	17 % (4)	4 % (1)	–	–
Interpretation and extensions								
Interpreting	–	–	–	–	13 % (3)	4 % (1)	**38 % (9)**	**92 % (22)**
Extending and predicting	4 % (1)	–	–	8 % (2)	29 % (7)	21 % (5)	21 % (5)	**33 % (8)**

In initial and final reports in percentages, the number of cases is in parentheses; there were twenty-four cases in total the flow chart is logically correct. This makes the construction of the electromagnetic induction law quite understandable and enables evaluation of the justification of each step.

As can be seen from the results in Table 8 that only in three cases (13 %), the initial reports were partly coherent; the rest of the cases consist of fragmented statements, experiments, models, and notions related to the induction law, but how the new knowledge is actually constructed and justified remains unclear. In the final reports, in eight cases (33 %), the construction and justification of the induction law was explained in detail and in a clear way (coherent), and nine cases (38 %) had partial coherence, but in seven cases (29 %), the reports still lacked coherence. As the results show, besides using and applying more experiments and interpretative models in different stages of forming the electromagnetic induction law, there is also clear development in the way they are used and applied in the reports. That means that the formation of electromagnetic induction law was better argued and justified in the final reports; the initial reports were more descriptive than constructive. However, only 33 % of final reports were coherent, so the task of arguing and justifying the formation of induction law was clearly demanding for most of the students.

5.3 Knowledge Justification

Finally, the pattern of knowledge justification in students' reports was examined. The learning tool is based on the generative justification of knowledge (Koponen and Mäntylä 2006), so it is expected that this way of justifying knowledge also appears in students' reports. If applied as it is supposed to be, the learning tool "forces" students to use both experiments and theory through models to justify the formation of knowledge. Other methods, which were seen in the reports, included consequential (emphasis on theory and models) and inductive (emphasis on experiments) justification of knowledge. The categories of knowledge justification are as follows:

1. *Generative.* Both experiments and theory, through use of models, are intertwined when justifying the induction law.
2. *Consequential.* Only theory and models guide the justification of knowledge and experiments are used only in verifying theoretical knowledge claims.
3. *Inductive.* Through experimentation and experiments, new knowledge claims are generated and annexed to theory.
4. *Undefined.* There is no recognizable pattern in the justification of knowledge in the report; it is more a collection of statements and facts without any relation between them.

The frequencies of different ways of justifying knowledge in students' initial and final reports are presented in Table 9. Although the features of certain ways of justifying knowledge were recognized in students' reports, they were not often presented properly. This is due to the difficulties in the overall coherence discussed above. In initial reports, half of the students justified the formation of induction law in a consequential way. This was expected, because in textbooks and in instruction, consequential knowledge justification is often applied. In 25 % of the initial reports, the induction law was used to justify experiments

Table 8 Categories of overall coherence in students' reports (n = 24)

Category	Initial	Final
Coherent	–	**33 % (8)**
Partly coherent	13 % (3)	**38 % (9)**
Incoherent	**87 % (21)**	29 % (7)

(inductive) and in 21 %, there was no clear justification. In final reports, most of the students (71 %) justified the formation of induction law in generative ways, which means that they used experiments to generate the induction law. In these cases, models were used in interpretative ways to mediate between experiments and theory throughout the process.

6 Discussion

Initially, students usually introduced one qualitative experiment, or just described the induction phenomenon at a general level. The continuation from a qualitative to a quantitative level was usually rather weak: qualitative and quantitative experiments were scarcely related. In final reports, the qualitative experiments were mainly used in an exploratory way and instead of one experiment, a set of qualitative experiments were discussed. The number of reports where qualitative experimentation was used in designing the quantitative experiment increased in the final reports. In the use of models, there was a development from the descriptive function to the form of reasoning, where relations were drawn from the theory to experiments, and vice versa; the models were used to mediate between experiments and theory. The results also show that, in most cases, the overall coherence of reports clearly developed during instruction. This means that students improved in describing how the electromagnetic induction law can be formed using physical knowledge using experiments and models.

The initial reports were made based on the knowledge that the students possessed at that time, with the help of textbooks and other resources. This shows that, even after taking university courses on electromagnetism, the conception of the electromagnetic induction law and how it can be formed poses difficulties for pre-service physics teachers. Applying the historical cognitive processes involved in the formation and development of electromagnetic induction to the contemporary teaching of pre-service physics teachers seems to lead more rational and coherent argumentation in students' reports at the level of both experimentation and reasoning, and knowledge justification. The results of this study seem to support the value of the cognitive-historical approach in science education, as originally suggested by Nersessian (1992), as long as the restrictions of the use of history of science, discussed by Seroglou and Koumaras (2001), are taken into account.

In this study, the electromagnetic induction law is only discussed at the macroscopic level; the next phase would include examination at the microscopic level in order to get a more complete picture of electromagnetic induction, as Guisasola et al. (2011) have discussed. As can be seen from the results (Tables 3 and 4), the students make only little use of the magnetic field lines. In addition, only one-third of the final reports were coherent (and in those, few ambiguities were allowed). One reason for the incoherencies was the treatment of the magnetic flux. It often suddenly appeared in the reports without a solid justification. According to Chabay and Sherwood (2006), one difficulty in understanding the induction law is due to the treatment order of the magnetic flux. They also suggest omitting the field line model because

Table 9 Categories of knowledge justification in students' reports (n = 24)

Knowledge justification	Initial	Final
Generative	4 % (1)	**71 % (17)**
Consequential	**50 % (12)**	8 % (2)
Inductive	25 % (6)	8 % (2)
Undefined	21 % (5)	13 % (3)

it causes more difficulties than it solves; this is more possible at the university level where the integral calculus is used. In this study, however, electromagnetic induction is handled at the upper secondary school level and the easiest way to understand the magnetic flux is through the field line model. The results suggest that the problem of implementing the magnetic flux in a justified and broadly understood way might be a consequence of a poorly understood and applied magnetic field line model. For Faraday, the field lines were powerful visual reasoning tools, and they also formed the basis for Maxwell's mathematicization of the field concept (Nersessian 1992; Tweney 2009).

Designing and using cognitive-historical reconstruction of the electromagnetic induction law within the DRP framework (Mäntylä 2011) offers one didactic approach that reduces the gap between teaching and learning the electromagnetic induction, as suggested by Guisasola et al. (2011).

7 Conclusions

The history of physics has been used in different ways in physics education. In this study, a cognitive-historical way of using historical concept formation is introduced. This proposed approach highlights the importance of recognizing the historical cognitive processes that were essential for the creation of new scientific concepts and which leading to conceptual change from an educational perspective. These recognized processes can serve as scaffolding in designing present teaching approaches because of the similarities in the creation of concepts and in the conceptual development of learners. However, the historical processes must be adapted to contemporary teaching so that the instruction forms a coherent whole, taking into account both content-based and didactical aspects.

In practice, the experiments and reasoning involved in the experimentation used in the reconstruction were similar to the experiments and reasoning that Faraday used. The historical experiments were adapted so that the modern measurement devices were used. Faraday flexibly varied and improved the experimental set-up or circumstances, and conducted a set of experiments to explore phenomena. In the reconstruction, there was no long chain of improved experiments, but variation in complementary experiments was included. The main emphasis was to include the essential cognitive processes in order to stress the unique features of induction phenomena.

The results show that the experiments and models found an essential role in students' argumentation in justifying knowledge, which was not initially the case. In addition, instead of only remembering the formula of the induction law, students better understood why the law is the way it is and its origin. Therefore, cognitive-historical reconstruction supports conceptual development for pre-service physics teachers' understanding of the electromagnetic induction law.

Acknowledgments This work was supported by the Academy of Finland through grant SA1133369.

Appendix 1: Task Given to the Students

Experiments and Models in Forming a Law: Electromagnetic Induction Law

The task is to explore how the electromagnetic induction law can be formed and how experiments and models are used in forming the law. In this, you can use the following questions as aids:

- What phenomenon is related to the law?
- What are the varying or constant features of the phenomenon that make it possible to identify the phenomenon, based on known theory?
- What are the varying or constant features of the phenomenon that form the basis of a quantifying experiment?
- What are the essential quantities in the case of induction law, and how are they measured?
- How is the law quantified? Short description and/or picture of the setup.
- What theory or models enable the interpretation of the experiment?
- How the law is incorporated to the existing theory?
- What kind of position does the law obtain in the structure of physics knowledge (e.g., independent, derived, restricted, general)?

The formation of the electromagnetic induction law is presented as a flow chart, which is complemented with a separate essay. DRP was discussed in the lectures (the flow chart in Fig. 2 without the induction law related content) and is used as a basis for the flow chart. The essay explains or elaborates upon the chart and is attached to the chart.

The level of discussion is commensurate with upper secondary school physics and it is assumed that the direct circuits, electro- and magnetostatics, are already familiar to you.

Appendix 2: Student Simeoni's Initial Report (Flow Chart in Fig. 3 and Essay)

Explanation of Chart

Homogeneous magnetic field is produced using Helmholtz coils. The magnitude of the field can be measured with a meter based on the Hall effect. The voltage is measured with voltmeter and the speed with using MBL.

A metal rod is placed to move in a homogeneous magnetic field. The rod is allowed to move steadily along the parallel conducting rails, and the resulting voltage between the rails is measured. The rod, the rails, and the field are set perpendicular to each other. By varying one factor at a time, it can be noticed that the measured induction voltage E is proportional to the distance between the rails L, the velocity of the rod v and the magnetic flux density of the field B (Fig. 4).

$E = LvB$ (electromagnetic magnetic induction law of motional emf)

From this, the general form is attained.

When the rod moves with velocity $v = \Delta x/\Delta t$, the area of the conducting loop A formed by the experimental setup changes with the velocity

$$\Delta A/\Delta t = L\Delta x/\Delta t = Lv$$

The expression of the induced emf is obtained in form

$$E = LVB = \Delta AB/\Delta t$$

A new quantity is introduced, the magnetic flux permeating through the loop

$$\Phi = AB$$

and the following form is obtained

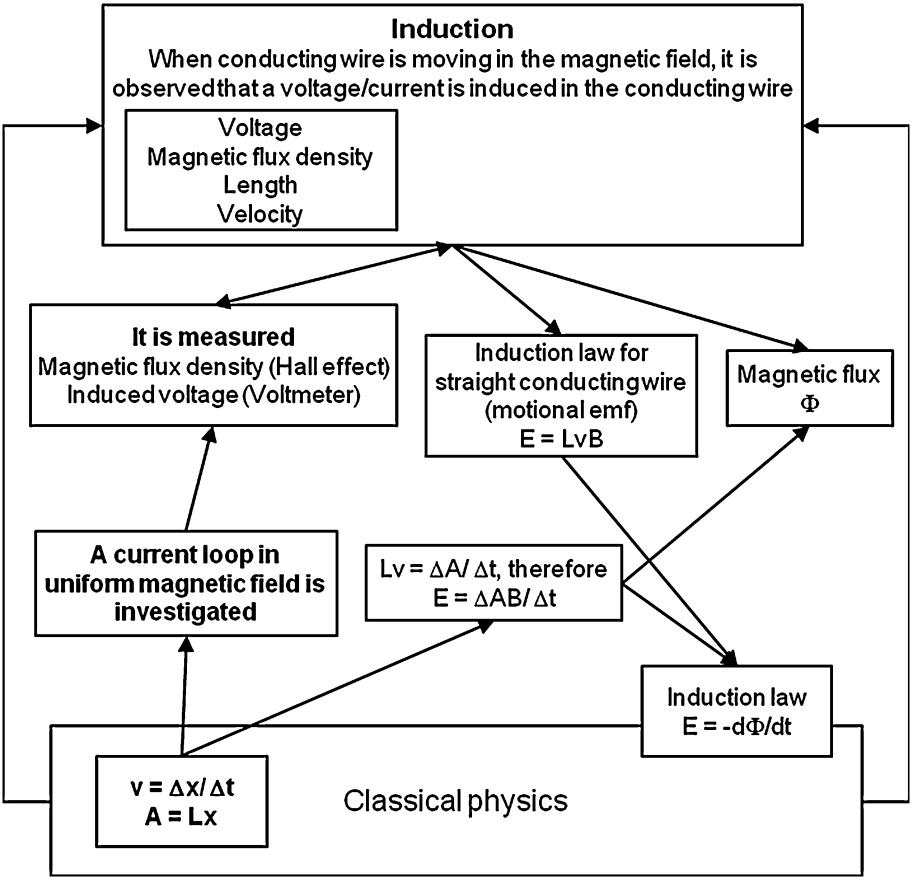
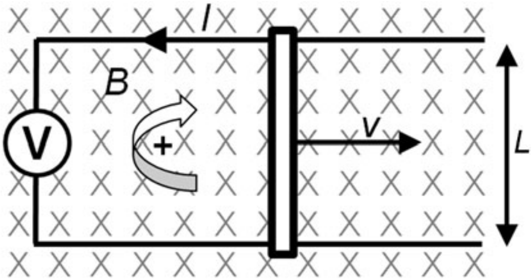


Fig. 3 Flow chart in Simeoni's initial report

Fig. 4 Picture of the setup of the quantitative experiment



$$E = \Delta\Phi/\Delta t$$

because the induced voltage tends to always resist the change, the induction law is obtained

$$E = -d\Phi/dt$$

This form is known as Faraday's and Henry's law. The law applies to all forms of magnetic induction, regardless of the cause of the change in magnetic flux due to the conductor's motion, the movement of the source of the field, or the change of the field.

Appendix 3: Student Noora's Final Report (Flow Chart in Fig. 5 and Essay)

Explanations

Experiment 1

The qualitative experiments are conducted using coils, bar magnets, current sources, and ammeters. Such ammeters are used, where the direction of current can be observed.

First, the poles of test coil are connected through the ammeter. A bar magnet is moved through the coil back and forth. It is observed that when the magnet is moving, there is current in the coil. If the magnet is not moving, the current disappears. Similar results are also obtained so that the magnet is stationary and the coil is moved. The electric current is the bigger, the faster the magnet is moved.

In the second experiment, two coils are set side by side, from which the other, "field coil", is connected from its poles to the current source. The other coil, "test coil", is connected to an ammeter. A current is observed in the test coil if one of the coils is moved. The magnitude of the induced current in the test coil depends now on the magnitude of the current in the field coil.

In the third experiment, two coils are also used. The field coil is connected with the current source and a switch and the test coil is connected with the ammeter. When the switch of the field coil is on and the current is moving in the coil, it is observed a current moving in the test coil. When the switch is released, the current is moving in the opposite direction. The phenomenon can be made more strength using joint iron bar in the coils.

Based on the first and second experiment, it could be thought that the current induced in the test coil somehow depends on the movement of the coil or magnet. However, the third experiment shows that this is not the case. Clearly, only the change of magnetic field is essential. From the directions of induced currents, it is observed that the direction of the induced current is such that it resists the change of magnetic field that has caused the current (Fig. 6).

Experiment 2

An adjustable current source, an ammeter and a field coil are connected to each other. The test coil is connected to the voltmeter. The current in field coil and the voltage in test coil are measured using computer. The current in field coil is changed using the adjustable current source (Fig. 7).

Explanation 3

It is observed that that the current's rate of change in field coil is proportional to the voltage induced in the test coil. Thus, $U_t \sim dI_f/dt$. As in the case of the qualitative experiments, here, it can also be observed that the direction of the induced voltage is such that is resists the change of magnetic field.

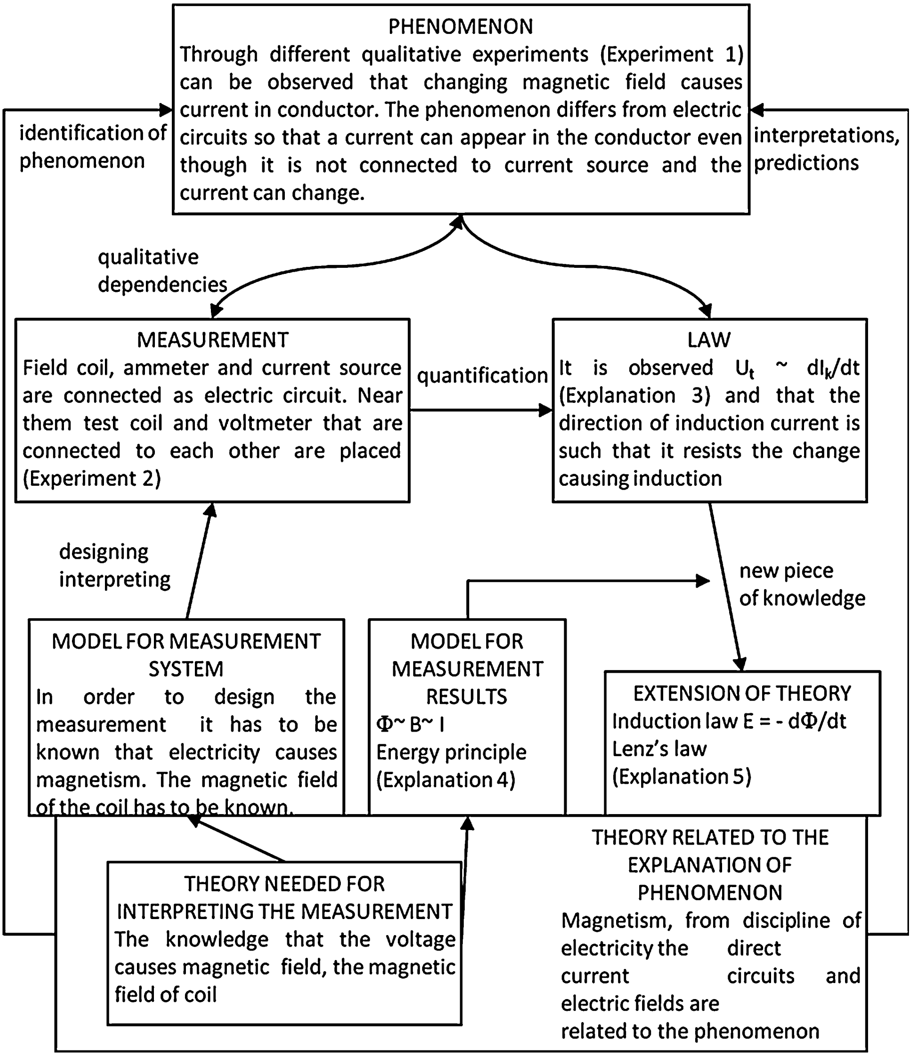


Fig. 5 Flow chart in Noora's final report

Explanation 4

Magnetic flux, Φ, and magnetic flux density, B, are proportional, so $\Phi \sim B$. On the other hand, according to the Biot-Savart law, the magnetic flux density, B, and current, I, are proportional to each other, $B \sim I$. Thus, $\Phi \sim B \sim I$.

According to the energy principle, the energy cannot disappear or arise out of nothing. So, the induction current consumes energy, e.g., in order to outdo resistance. This energy must be received from the system causing induction. The direction of the induction phenomenon must be opposing the change causing it, because the cause of induction must do work in order to outdo the counter-effect of the induction current.

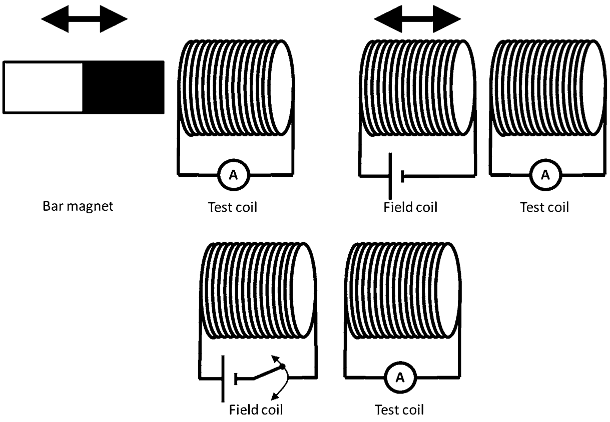
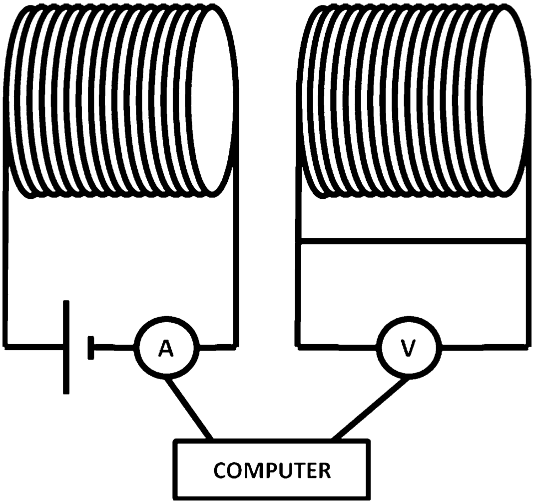


Fig. 6 Pictures of the setups of qualitative experiments in Experiment 1

Fig. 7 Picture of the setup of the quantitative experiment in Experiment 2



Explanation 5

Induction law E = −dΦ/dt, where E is the induced voltage and Φ is the magnetic flux. According to Lenz's law, the direction of induction current is such that it resists the change causing the induction.

Induction law is an independent law; it cannot be derived from other laws of electromagnetism. Induction law combines the disciplines of electricity and magnetism. The electric current induces magnetic field, the induction is the inverse phenomenon of this, and the changing magnetic field causes electric current.

Appendix 4: Categorization Examples

Table 10 shows how contents in Simeoni's initial report (Appendix 2) and Noora's final report (Appendix 3) are categorized.

Table 10 Categorizations of Simeoni's and Noora's reports

Category	Categories in Simeoni's report	Categories in Noora's report
Qualitative experiments	–	Bar magnet and coil: Moving bar magnet near or inside the coil Effect of movement or the speed of movement Moving the coil when magnet is stationary Two coils: Moving primary coil, secondary coil stationary Two coils: Changing the current/voltage in primary coil Direction of phenomenon Effect of the magnitude of current or the turns of coils Effect of iron bar inside the coil
Quantitative experiments	Conducting rod sliding on conducting rails in uniform magnetic field	Two coils: The electric current in primary coil and the voltage in secondary coil are measured as a function of time
Descriptive models	A current or voltage is induced in current loop or conducting wire when it moves in (uniform) magnetic field	–
Interpretative models	Experiment or model of conducting rod sliding on conducting rails in uniform magnetic field: Deriving Faraday's induction law from motional emf of moving conductor Generalization of results: Faraday's induction law as a basic experimental law of electrodynamics	Induction phenomena occurs only when magnetic field or magnetic flux changes based on qualitative experiments Direction of induced current (Lenz's law) $\Phi = BA$ or Gauss's law Biot-Savart law or Ampère's law Generalization of results: Faraday's induction law as a basic experimental law of electrodynamics
Phenomenon: identifying	–	*Interpretative Model:* The description in "Phenomenon" box in flow chart
Phenomenon: observing	*Descriptive model:* The description in "Induction" box in flow chart	*Descriptive Model:* The description in "Phenomenon" box in flow chart *Qualitative Experiment(s):* Descriptions of experiments in "Experiment 1" in explanations
Phenomenon: decomposing	–	*Qualitative Experiment(s):* Descriptions of experiments in "Experiment 1" in explanations *Interpretative Model:* Last paragraph in "Experiment 1" in explanations

Table 10 continued

Category	Categories in Simeoni's report	Categories in Noora's report
Measurement: designing	–	–
Measurement: conducting	*Quantitative experiment:* Description of the experiment of the metal rod on conducting rails	*Quantitative Experiment:* Description of experiment in "Experiment 2" in explanations
Interpret and extens: interpreting	*Interpretative model:* Deriving induction law from experimental law E = LvB	*Interpretative Model:* Description in "Explanation 4" in explanations
Interpret and extens: extending and predicting	*Interpretative model:* Last sentence of interpreting and generalizing the induction law	*Interpretative Model:* The description in "Model for measurement results" box in flow chart, Last paragraph of "Explanation 5" in explanations
Coherence of knowledge claims	Incoherent	Coherent
Knowledge justification	Consequential	Generative

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