INVESTIGATING LEARNING IN ENGINEERING AND IN TECHNO-SCIENCE AS A MATERIAL DISCURSIVE PRACTICE

AIMS AND OBJECTIVES

The production of knowledge in science and engineering in modern society is technologically embodied. This is more than to say that science uses instruments (technologies), but it uses these technologies in unique and critical ways. According to Alfred North Whitehead (1963, p. 107, my italics):

> "The reason we are on a higher imaginative level [in modern science] is not because we have a finer imagination, *but because we have better instruments*. In science, the most important thing that has happened in the last forty years is the advance in instrumental design…a fresh instrument serves the same purpose as foreign travel; *it shows things in unusual combinations. The gain is more than a mere addition; it is a transformation*".

Learning is described by Marton and Tsui (2004) as developing a vision: "Arranging for learning implies arranging for developing learners' ways of seeing or experiencing, *i.e., developing the eyes through which the world is perceived*.

Given this fact an important issue for educational research is how students and professionals in a specific discipline acquire a "professional vision" (Goodwin, 1994). As mentioned above, a central characteristics of learners' and professionals' experience of our world in engineering and in most sciences is that experience should not be seen as a direct experience *human – world*, but as an experience shaped by the use of physical and symbolic tools, i.e. artefacts (spelled artifact in U.S. English). The concept of mediation and mediating tools could be represented diagrammatically as: *Human – mediating tools (artefacts) – world*. Questions about the role of technology (artefacts) in everyday human experience include:

– How do technological artefacts affect the existence of humans and their relationship with the world?
– How do artefacts produce and transform human knowledge?
– How is human knowledge incorporated into artefacts?
– What are the actions of artefacts?

The structure of an artefact as well as learning to use an artefact changes the structure of human interaction with the world and hence is closely related to learning and hence one would expect that the role of technologies for learning should have been extensively investigated. However, with a few exceptions, the role of instrumental technologies in student learning in laboratories are rarely studied or problematised in science educational research. This is in line with the "[traditional belief] that … instruments and experimental devices … *per se* … has no cognitive value" (Lelas, 1993, pp. 423-424, italics in original), i.e. in traditional beliefs about science the technological means by which nature is perceived leaves no trace in our conceptions of nature (e.g., Kroes, 2003). Popper, for an example, restricted his epistemology to the "world of language, of conjectures, theories, and arguments" (1972, p. 118). A consequence of this is that the role of instruments is often neglected or taken-for-granted and the emphasis is placed only on concepts and ideas. However, neglecting the role of instruments (i.e. technological artifacts) in science leads to naïve realism or to naïve idealism (Ihde, 1991; Ihde & Selinger, 2003). It also leads to that educators will be 'blindfolded' in regard to critical features of the role of experimentation in a curriculum.

As argued above and in the following sections there are a need to investigate students' conceptual learning in engineering and in techno-science[1] as a material-discursive-practice. Specially, we will study student's *practical achievement* of understanding through the *use* of symbolic and physical artefacts as discursive tools in lab-work.

[1] The term techno-science is used to denote the dependency in modern science of technology and its embodiment in technological apparatus (cf. Tala, 2009).

OVERVIEW

The previous sections provide a brief introduction and presentation of the objectives and aims of the project. With the purpose of giving an overview of both the empirical domain and central research issues related to student learning as a material-discursive-practice are expanded in the following sections.

Research into engineering students' learning is internationally a rather new field of research. In recent years research studies into critical factors for learning in engineering education have started to emerge and engineering education research (EER) as a field of research have started to mature (Baillie & Bernhard, 2009; Borrego & Bernhard, 2011). Nevertheless the project can build on earlier research in science education, education, science studies, philosophy of scientific experiments and philosophy of technology.

Almost thirty years ago Hofstein and Lunetta (1982, p. 201) in a review argued that the "role of the laboratory in science teaching [were a] neglected [aspect] of research" and didn't reflect the "central and distinctive role [the laboratory has been given] in science education, and [the] rich benefits in learning from using laboratory activities [suggested by science educators]". Laboratory learning activities was seen by Hofstein and Lunetta (1982, pp. 201-202) as "concrete experiences with objects and concepts", by Trumper (2003, p. 655) as "direct experience with physical phenomena" and in the National Research Councils' *America's Lab Report* (Singer, Hilton, & Schweingruber, 2006, p. 31) as "opportunities for students to interact directly with the material world … using the tools, data collection techniques, models, and theories of science." I.e. observation in the laboratory is seen as something unproblematic and seen as a "direct experience" of the phenomena studied. The role of experimental technologies for student experiences and learning is seldom discussed and equipment is seen as something that is just "manipulated" (e.g. Lunetta, 1998, p. 250; Lunetta, Hofstein, & Clough, 2007, p. 403). Hucke and Fischer (2002, p. 206) expressively describes "object related" action (manipulating objects) as a low complexity-level of cognition while "concept related" (manipulating ideas) is high complexity-level. The view that experimental technologies have little cognitive value is hence expressed in at least three recent reviews and books (Lunetta, et al., 2007; Psillos & Niedderer, 2002; Singer, et al., 2006). As noted by Ihde (1991) and Kroes (2003), for example, observation is not generally regarded as problematic in positivist approaches and from the anti-positivist perspective, the praxis-ladenness of observations tends to be overlooked. Kroes expresses this as follows:

> "In [the traditional] view, the physicist is essentially a passive observer in experiments: once the stage is set he just observes (discovers) what is going to happen."

Much of the theoretical framework of science education research is based on cognitivist and mentalist ideas that could be described as based on "the presumption that all psychological explanation must be framed in terms of internal mental representation" (Still & Costall, 1987, p. 2). Hence, in cognitivist theories "technology is nearly invisible", however in "postcognitivist" theories such as activity theory, distributed cognition, actor-network theory, and phenomenology "a major point of agreement … is the vital role of technology in human life [and a criticism] of mind-body dualism" (Nardi & Kaptelinin, 2006, pp. 195-197). In figures 1a and 1b are displayed an illustration of the view of the role of technologies found in most science education research, in educational research based on cognitivist assumptions and in traditional philosophy of science (Bernhard, 2008).

On the other hand in praxis philosophies and in theories focusing on human practice such as in the socio-cultural theory, cultural history activity-theory (Cole & Derry, 2005) and in Dewey's pragmatism (Hickman, 1990) tools and mediation are key concepts. The central thesis is that the structure and development of human psychological processes are co-constituted by the interaction with tools. These tools (artefacts) are *simultaneously material* and *ideal/conceptual*. The role of artefacts is often illustrated by a mediation triangle such as in figure 1c to illustrate that experience is transformed. Engeström and Miettinen (1999, p. 29) claim that a "serious study of artifacts as integral and inseparable components of human functioning" is needed. This also done in naturalistic studies of scientist in actions, for example in the paper "seeing in depth" by Goodwin (1995), there are also ample discussion of the instruments the different scientists used and for what purpose in contrast to the neglect of instrumental technologies found in most educational research.

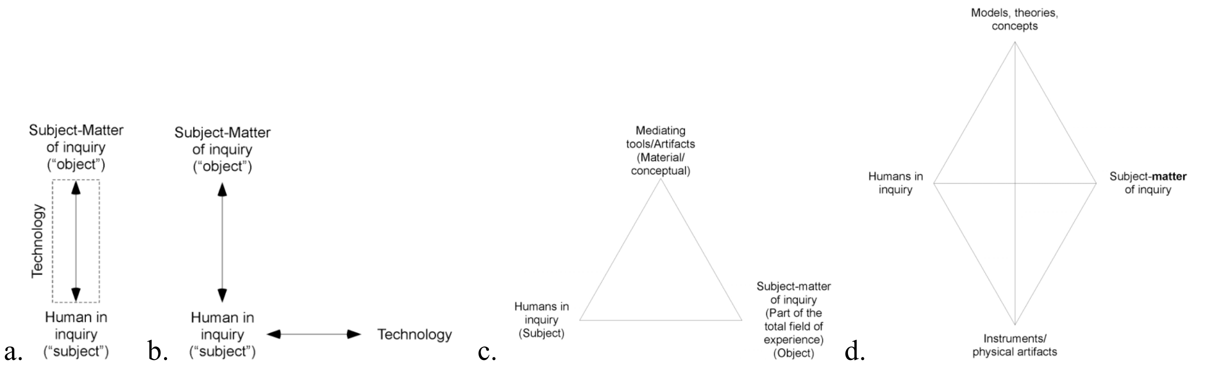


Figure 1. a) A "Transmissive" view of technology where technology is seen merely as a vehicle for transmission of information. b) An "Auxiliary" view where technology is seen merely as a provider of information or support. c) Mediation triangle adapted from Cole (1996). d) A revision of the mediation triangle to analytically differentiate between physical and symbolic tools in artefact mediated action.

Criticism of the neglect experimental technologies in analysis could also be found in the emergent field of philosophy of scientific experimentation. An early critic was Ian Hacking (1983) who argued that "philosophers of science constantly discuss theories and representation of reality, but say almost nothing about experiment, technology, or the use of knowledge to alter the world". Twenty years later Radder (2003, pp. 1-8) argued for "a more developed philosophy of scientific experimentation" and claimed:

> "The fact that many scientists … spend most of their time doing experiments of various kinds is not reflected in the basic literature in the philosophy of science. … Thus, the philosophy of experimentation is still underdeveloped …There has been a strong tendency to take the production of empirical knowledge for granted. … In sum, if philosophers keep neglecting the technological dimension of science, experimentation will continue to be seen as a mere data provider for the evaluation of theories". (cf. Baird, 2004; Gooding, 1990; Harré, 2003; Kroes, 2003)

In the philosophy of technology some researchers as Don Ihde (Ihde, 1979, 1991, 1998, 2009; Ihde & Selinger, 2003; Selinger, 2006) has studied experimental technologies. He has extended and synthesized ideas from phenomenology and pragmatism into a post-phenomenology. According to Ihde all science in its production of knowledge is technologically embodied and perception is co-determined by technology ("Instrumental realism", Ihde, 1991) but technology on the other hand uses the theories of science. Hence the term techno-science is often used to denote present days symbiotic relationship between science and technology. According to the analysis of micro-perception performed by Ihde experience is transformed by the mediating technology and the technology actively shapes the relationship between humans and their life-world by placing certain aspects in the foreground (and others in the background) and also by making certain aspects of reality visible that otherwise would be invisible. Ihde has categorised mediated perception using technologies as embodied, hermeneutic or alterity relationship.

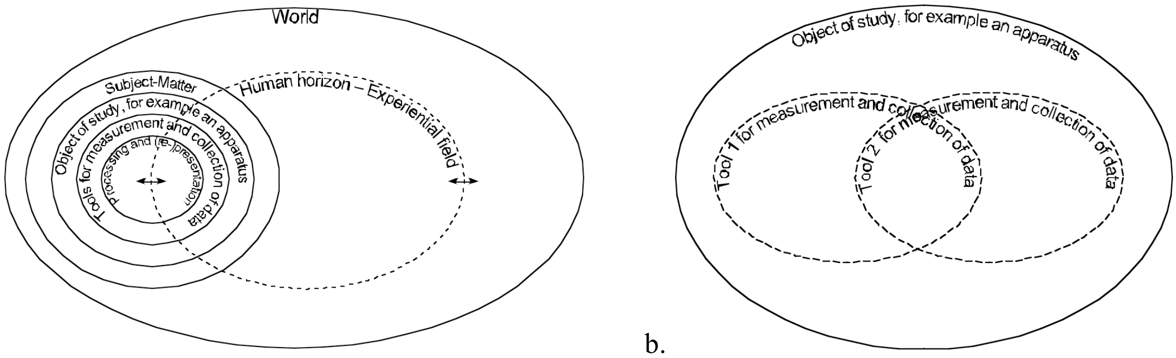
Scientists themselves in opposition to dominant views have also put forwards criticism of the neglect of experimental technologies. In the philosophy-physics of Niels Bohr (1958) it is suggested that we should use the word "*phenomenon* exclusively to refer to the observations obtained under specified circumstances, including an *account of the whole experimental arrangement*". Agencies of observation (the technology) and the object studied (some aspect of the world) cannot meaningfully be separated in Bohr's view. Only concepts that are defined by their specific embodiment in a material arrangement that produces a reading that can be read by a human are meaningful. Building on Bohr's view Karen Barad (e.g. 2007) have argued that an *material-discursive* analysis of practice is needed. Furthermore Tala (2009, p. 275) has studied scientific practice in nanophysics as an example of techno-science and argued that science education should be based on a "scientifically sound and authentic content [of science as] the necessary starting point" taking into account for example the use of technologies. In a similar vein David Gooding (1990, p. 27) several years ago stressed that "theories of learning and representation should be compatible with our knowledge of how scientist gain and use information about reality".

PRELIMINARY RESULTS

Probe-ware systems were introduced into physics teaching almost three decades ago and are good examples of the use of interactive technology in physics education (Tinker, 1996). They consist of a sensor or a probe connected to a computer, which analyses data collected by the probe, and transforms experimental data directly into a graph on the computer screen. When using probe-ware, students can perform experiments using a range of different sensors to gather data on variables such as force, motion, temperature, light or sound. The *simultaneous* collection, analysis and display of *experimental* data are sometimes referred to as *real-time* graphing. The immediacy of this technology allows the design of labs that foster a functional understanding of physics most effectively (e.g. Bernhard, 2005, 2010; Euler & Müller, 1999; Hake, 1997; Sokoloff, Laws, & Thornton, 2007; Thornton, 1996, 1997; Tinker, 1996). In 1999, Euler and Müller (1999) reported at the ESERA-conference in Kiel that the so called microcomputer based laboratory (MBL) using probe-ware is the only method using computers in physics curricula that has a proven positive learning effect. In Swedish settings the good learning results have been repeated (Bernhard, 2005, 2010).

The success of the MBL-based curricula has been explained in terms such as "active learning environments" and that the tools "allow students to find answers directly from the physical world", allow "immediate feedback" through "real-time graphing" and "[reduce] the drudgery of data collection and manipulation" (e.g. Thornton, 2008). However as demonstrated in Bernhard (2003) probe-ware (MBL) technology could be implemented in ways that results in less good results on conceptual tests. Furthermore as demonstrated by Lindwall and Ivarsson (2010) and Bernhard (2011a) other learning environments share the attributes used to explain the success of the MBL-curricula, but without as good learning results. Therefore the good learning must be explained in other terms than is usually presented in the literature. A fine grained analysis of students courses of action and of task-structure (Bernhard, 2005, 2010, 2011a, 2011c; Carstensen & Bernhard, 2009) in successful labs suggests that the good learning results in some learning environments, and not in other, could be understood in light of the necessary conditions for learning according to Variation theory (e.g. Marton & Pang, 2008; Marton & Tsui, 2004).

As mentioned above Bernhard (2003) had made an analysis of different uses of probe-ware technology in mechanics labs and had argued that the technology could serve as a "cognitive tool (sense making)". Although no detailed empirical analysis of the cognitive role of the experimental technologies used in the labs studied were presented in that study it was argued that we in educational research must focus as much on the cognitive aspects as on "pure" technological aspects of technologies. Preliminary empirical studies in the field of engineering education (Bernhard, 2007, 2008, 2010, in press) suggest that the role of technologies for student learning is dependent upon the fact that the technology used places some aspects of reality in the foreground, others in the background, and makes certain aspects visible that would otherwise be invisible. Different technologies have different affordances for discernment and hence the possibilities for learning different objects of learning are dependent upon the technologies available or made available to students. Findings from existing research show that student' interactions with artefacts and the aspects of the world to be learned are complex. Briefly it is suggested that the situation in successful labs could be described as a situation involving embodiment as well as hermeneutics there human-artefact-complexes and world-artefact-complexes could be seen as overlapping: (Human ⇔ {Artefacts) ⇔ World}. There is, however, ample evidence that in many cases it is very difficult for students to make connections between artefacts and the world and the situation could be seen as the ultimate alterity relationship: Human ⇔ Artefacts ~~(⇔ World)~~. It has been demonstrated that technologies are neither deterministic tools causing pre-determined learning nor neutral tools.



a. b.

Figure 2. Illustration of the selective horizons of experimental technologies in relation to human life-world.

In a preliminary study (Bernhard, 2011b) high-school level physics labs were investigated there on the surface the same physics were studied (accelerated motion) but different , but commonly used, experimental technologies were used as "agencies of observation". It is shown what possible could be "seen" by students were dependent on the technology used and some technologies did not allow that some common "misconceptions" were addressed in the lab. Although on one level the same physical object were studied the "learning space" constituted were different. To borrow a concept from phenomenology different technologies has different horizons as illustrated in figure 2b.

In both engineering and physics education, a common objective is that students should *learn* to *use* theories and models in order to understand the *relation* between theories and models, and objects and events, and to develop holistic, conceptual knowledge. During lab-work, students are expected to *use*, or *learn to use*, symbolic and physical tools (such as concepts, theories, models, representations, inscriptions, mathematics, instruments and devices) in order both to understand the phenomena being studied, and to develop the skills and abilities to use the tools themselves (Psillos & Niedderer, 2002; Tiberghien, 1998). In education research it is common to investigate "misconceptions" of "single concepts". We have analysed engineering students learning in an electric circuit theory course and argue that this view is problematic and inadequate. Instead we propose a model where learning is seen as the *learning of a complex concept*, i.e. a "concept" that makes up a holistic system (i.e. a *whole* made up of interrelated *parts*) (Bernhard, Carstensen, & Holmberg, 2010; Carstensen & Bernhard, 2004, 2007, 2008, 2009). Examples of analysis are presented in figure 3. This model can be used as a tool for representing and analysing students' material-discursive practice showing the multitude and complexity of actions students do or are supposed to be able to do using symbolic as well as physical entities and tools to develop a professional vision. The model is a much more fine-grained analysis than is displayed in figure 1d and one conclusion is that it's not adequate to discuss knowledge in terms of a dichotomy between knowing and not knowing or between theory/model and "reality". It should be noted that based on empirical data the model is not hierarchical but circular (cf. Tala, in press, who found a circular model in the context of nanophysics).

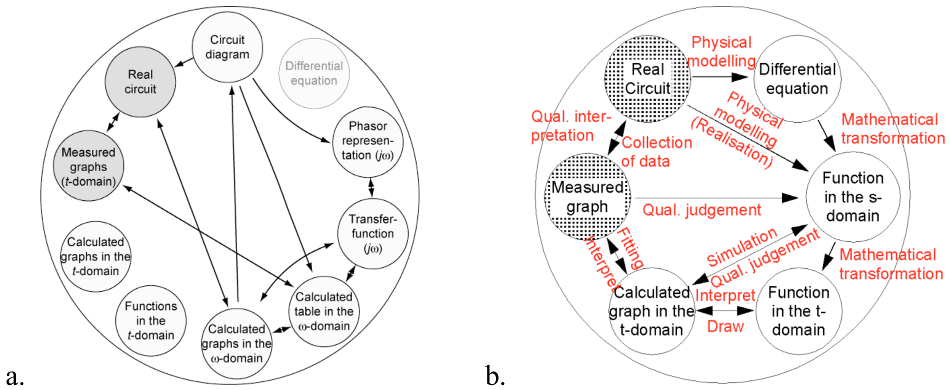


Figure. 3. Student learning in electric circuit theory analysed as a material-discursive-practice using the model of "learning of a complex concept" displaying the complexity of student learning. The shaded circles represent knowledge located in the "world" of objects/events and the other circles the "world" of theories/models according to a categorization proposed by Tiberghien (1998). In figure 3a the lived object of learning in an AC-electricity lab is analysed and in figure 3b in an transient response lab. It can be noted that in figure 3b the items of "real circuit" and "circuit diagram" from figure 3a have been fused into one item.

PROJECT DESCRIPTION

The point of departure of this project is that the study of the role of technologies for student learning in lab-work is, with few exceptions, neglected in engineering and science education research. In this study we will study of student's activities in labs using video-recordings.

Firstly we will study the role of technologies, such as instrumentation, as devices for the production of representations (inscriptions). Especially in electrical engineering students use many different instruments in their work for the practical achievement of understanding such as oscilloscopes and other devices. By analysing video-recordings we will study students' use of technologies and representations – what is brought to the fore by the technologies, what is possible to "see", what is difficult to "see" and what is impossible to "see". How are students using experimental technologies to make sense during experimental investigations? (An early example of a tool perspective is Nemirovsky, et al., 1998) The analytic approach will be informed by methodology for analysing video based on the traditions of ethnomethodology and conversation analysis (see for example Lindwall, 2008) but also phenomenological variation (Ihde, 1986) will be used to analyse technologies. We will study what patterns of variance and invariance are possible by the physical setup of and the instruments used in different labs. In particular, we plan to analyse differences in possibilities for critical variation and discernment and relate it to "instrumental realism" (Ihde, 1991).

Secondly we will study the material-discursive-practice in lab-work using the model of "learning a complex concept" described above. We will especially study if this methodology for analysis could illuminate the complex process of establishing a conceptual whole and we suggest that it can provide another view on what changes in "conceptual change". Our earlier data suggest that the model of 'learning a complex concept' could be used to find critical features that should be varied according to Variation theory. We will study this since this provides a means for finding a method for designing conceptual labs. This project is related to the first one since physical artefacts and inscriptions are an integrated part of the model of "learning of a complex concept".

For the analysis of student's courses of action we have earlier recorded video of engineering students lab-work in "innovative" courses in mechanics and in electric circuit theory and teacher students lab-work in mechanics. Some of these recordings have been used to analyse task-structure and instructions using variation theory as a theoretical framework. These recording will be analysed using the approach presented above. However, these recordings are from "innovative" courses and hence data will be collected from student's uses of experimental technologies in selected courses in engineering and physics (as representing techno-science).

The first year of the project will mainly consist of recording, transcribing and annotating the material as well as reading relevant literature. Alongside this, preliminary analyses will be conducted. During the second year, the analyses will be further developed at the same time as complementary recordings are made. These findings and analyses will be presented at conferences such as EARLI, the Threshold concept symposium, Research in Engineering Education Symposium, ESERA and SEFI. During year three the studies will be completed and submitted for publication. The focus will be international journals such as the European Journal of Engineering Education, Journal of Engineering Education, Science Education, International Journal of Science Education, Journal of the Learning Sciences and Instructional Science, but book chapters and publications to a broader audience is also intended.

SIGNIFICANCE

As noted above engineering education research is a rather new field of research (Baillie & Bernhard, 2009; Borrego & Bernhard, 2011) and as such the proposed project will contribute to the development of scientific knowledge in this emergent field. In a more general sense there are very few empirical studies in any area of experimental sciences and engineering on the role of mediating technologies and materiality for student learning in lab-work and the development of professional skills. Outside techno-science and engineering professionals in many domains use mediating technologies (for example X-ray, microscopes and ultrasonic devices in the health sciences) to "see" with and hence the proposed project has potential to contribute to a field where very little is known. The proposed project will therefore possibly contribute to theory development as well as to contribute with knowledge that can be used to develop better labs and enhance student learning in universities and high-schools.

COLLABORATIONS AND NETWORKS

Although the project has an institutional basis at the Engineering education research group at the Department of Science Technology (ITN), Campus Norrköping, Linköping University, it takes advantage of the close co-operation with the research group in Visual learning and communication also at ITN and the research groups in science education, technology education, and the Swedish national graduate school in science, technology and mathematics education research (FontD) with institutional basis in the School of education. All these groups co-operate for a shared research environment in STEM-research with for example common seminars and doctoral courses.

The co-operation with Gothenburg University (especially associate professor Oskar Lindwall) is planned to continue. We will especially co-operate on ethnomethodological studies of students' practical achievements of understanding using technologies in laboratories and part of the proposed project share concerns with Lindwall's project *Illumination, magnification and verbalisation: Technologies and techniques in the learning of endodontics*, especially the theme "professional vision, visual representations and technological development". We will also co-operate with professor Caroline Baillie, University of Western Australia, regarding engineering students use of concepts and developing the notions of threshold concepts and complex concepts as analytic tools in engineering education research. A close partner in this project is profesora titular Margarita Holmberg (née Gonzalez Sampayo) at Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Mexico City. Linköping University is also co-applicant in the application *Training for Research on Engineering Education New Developments and Sustainability* (Marie Curie Training Networks) with Aalborg University and professor Anette Kolmos as leader.

The principal investigator of this project is former chairman of the Swedish Science Education Research Association and chairman of SEFI:s (European Society for Engineering Education) Working Group for Engineering Education Research. He is co-ordinator for a Nordic network in Engineering Education Research funded by NordForsk and associate editor for European Journal of Engineering Education. In these roles he has a leading role in the international Engineering education research community manifested in being one of the invited contributors to the centennial jubilee issue of Journal of Engineering Education (Borrego &

Bernhard, 2011) and one of the invited contributors to the forthcoming *Encyclopedia of the sciences of learning* (Bernhard, in press).

PART OF PROJECT COST

Of the estimated costs for this project 75% is applied from the Research council. The other 25% will be covered through the universities own budgets as for example the research part of positions and the support of research groups.

BUDGET

Funding is applied for release time for the principal investigator and for salaries for one research associate (part-time) and one doctoral student. Funding is also applied to enable professors Caroline Baillie and Margarita Holmberg to spend time as visitors in the group. Besides costs for participating in conferences and travel for national and international co-operations there will be costs associated with for example video recording, storage and analysis.

ETHICAL CONSIDERATIONS

The project will follow the ethical and legal guidelines provided by the Research Council, the Swedish Government and Linköping University. Since the data is considered not to contain "sensitive material" and data collection will take place during regular teaching sessions and not affect humans negatively aprovement according to the law (2003:460) regarding research involving humans is considered not to be necessary. As legally regulated, the recordings are owned by Linköping University. All material will be archived, stored and handled by the department of Science and Technology (ITN) in accordance with all relevant regulations and policies. Since the recorded activities involve identifiable people, the recordings have to be treated in accordance with the regulation of personal data (Personuppgiftslagen, 1998:204).

OTHER GRANTS

The principal investigator is co-ordinator for *Nordic network in Engineering Education Research (NNEER)* funded by NordForsk (2009-2012) and co-applicant Marie Curie Training Networks (EU) *Training for Research on Engineering Education: New Developments and Sustainability* with subproject conceptual learning in STEM.

REFERENCES

Baillie, C., & Bernhard, J. (2009). Educational research impacting engineering education. *European Journal of Engineering Education, 34*(4), 291-294.

Baird, D. (2004). *Thing knowledge: A philosophy of scientific instruments*. Berkeley: University of California Press.

Barad, K. (2007). *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning*. Durham: Duke University Press.

Bernhard, J. (2003). Physics learning and microcomputer based laboratory (MBL): Learning effects of using MBL as a technological and as a cognitive tool. In D. Psillos, K. P., V. Tselfes, E. Hatzikraniotis, G. Fassoulopoulos & M. Kallery (Eds.), *Science Education Research in the Knowledge Based Society* (pp. 313-321). Dordrecht: Kluwer.

Bernhard, J. (2005). *Experientially based physics instruction - using hands on experiments and computers: Final report of project 167/96*. Stockholm: Council for Renewal of Higher Education.

Bernhard, J. (2007). Thinking and learning through technology - Mediating tools and insights from philosophy of technology applied to science and engineering education. *The Pantaneto Forum, 27*.

Bernhard, J. (2008). Humans, intentionality, experience and tools for learning: Some contributions from post-cognitive theories to the use of technology in physics education. *AIP Conference Proceedings, 951*, 45-48.

Bernhard, J. (2010). Insightful learning in the laboratory: Some experiences from ten years of designing and using conceptual labs. *European Journal of Engineering Education, 35*(3), 271-287.

Bernhard, J. (2011a, June 26-29). *Investigating student learning in two active learning labs: Not all "active" learning laboratories result in conceptual understanding*. Paper presented at the ASSE Annual Conference, Vancouver.

Bernhard, J. (2011b, June 14-16). *Is the same science studied or not? A study of learning in a physics lab as a material-discursive practice.* . Paper presented at the NFSUN 2011, Linköping.

Bernhard, J. (2011c, September 27-30). *Learning in the laboratory through technology and variation: A microanalysis of instructions and engineering students' practical achievement*. Paper presented at the SEFI/WEE 2011, Lissabon.

Bernhard, J. (in press). Learning through artifacts in engineering education. In N. M. Seel (Ed.), *Encyclopedia of the Sciences of Learning*. New York: Springer.

Bernhard, J., Carstensen, A.-K., & Holmberg, M. (2010). *Investigating engineering students' learning – learning as the ‚learning of a complex concept'*. Paper presented at the IGIP-SEFI 2010, Trnava.

Bohr, N. (1958). *Atomic physics and human knowledge*. New York: John Wiley & Sons.

Borrego, M., & Bernhard, J. (2011). The emergence of engineering education research as a globally connected field of inquiry. *Journal of Engineering Education, 100*(1), 14-47.

Carstensen, A.-K., & Bernhard, J. (2004, 18-21 August). *Laplace transforms - too difficult to teach, learn and apply, or just matter of how to do it.* Paper presented at the EARLI sig#9 Conference, Gothenburg.

Carstensen, A.-K., & Bernhard, J. (2007, 22-24 June). *Critical aspects for learning in an electric circuit theory course - an example of applying learning theory and design-based educational research in developing engineering education.* Paper presented at the First International Conference on Research in Engineering Education, Honolulu.

Carstensen, A.-K., & Bernhard, J. (2008). Threshold concepts and keys to the portal of understanding: Some examples from electrical engineering. In R. Land, E. Meyer & J. Smith (Eds.), *Threshold concepts within the disciplines* (pp. 143-154). Rotterdam: Sense Publishers.

Carstensen, A.-K., & Bernhard, J. (2009). Student learning in an electric circuit theory course: Critical aspects and task design. *European Journal of Engineering Education, 34*(4), 389-404.

Cole, M. (1996). *Cultural psychology: A once and future discipline*. Cambridge, MA: Harvard University Press.

Cole, M., & Derry, J. (2005). We have met technology and it is us. In R. J. Sternberg & D. D. Preiss (Eds.), *Intelligence and Technology: The Impact of Tools on the Nature and Development of Human Abilities*. Mahwah: Lawrence Erlbaum.

Engeström, Y., & Miettinen, R. (1999). Introduction. In Y. Engeström, R. Miettinen & R.-L. Punamäki (Eds.), *Perspectives on activity theory* (pp. 1-16). Cambridge: Cambridge University Press.

Euler, M., & Müller, A. (1999). *Physics learning and the computer: A review, with a taste of meta-analysis.* Paper presented at the ESERA 1999, Kiel.

Gooding, D. (1990). *Experiment and the making of meaning: Human agency in scientific observation and experiment*. Dordrecht: Kluwer.

Goodwin, C. (1994). Professional vision. *American Anthropologist, 96*(3), 606-633.

Goodwin, C. (1995). Seeing in depth. *Social Studies of Science, 25*(2), 237-274.

Hacking, I. (1983). *Representing and intervening: Introductory topics in the philosophy of natural science.* Cambridge: Cambridge University Press.

Hake, R. R. (1997). Interactive-engagement vs traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics, 66*, 64-74.

Harré, R. (2003). The materiality of instruments in a metaphysics for experiments. In H. Radder (Ed.), *The Philosophy of Scientific Experimentation* (pp. 19-38). Pittsburgh: University of Pittsburgh Press.

Hickman, L. A. (1990). *John Dewey's pragmatic technology*. Bloomington: Indiana University Press.

Hofstein, A., & Lunetta, V. N. (1982). The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research, 52*(2), 201-217.

Hucke, L., & Fischer, H. (2002). The link of theory and practice in traditional and in computer-based university laboratory experiments. In D. Psillos & H. Niedderer (Eds.), *Teaching and Learning in the Science Laboratory* (pp. 205-218). Dordrecht: Kluwer.

Ihde, D. (1979). *Technics and praxis*. Dordrecht: D. Reidel.

Ihde, D. (1986). *Experimental phenomenology: An introduction*. Albany: State University of New York Press.

Ihde, D. (1991). *Instrumental realism: The interface between philosophy of science and philosophy of technology.* Bloomington: Indiana University Press.

Ihde, D. (1998). *Expanding hermeneutics: Visualism in science*. Evanston: Northwestern University Press.
Ihde, D. (2009). *Postphenomenology and technoscience: The Peking university lectures*. Albany: State University of New York Press.
Ihde, D., & Selinger, E. (Eds.). (2003). *Chasing technoscience: Matrix for materiality*. Bloomington: Indiana University Press.
Kroes, P. (2003). Physics, experiments, and the concept of nature. In H. Radder (Ed.), *The philosophy of scientific experimentation* (pp. 68-86). Pittsburgh: University of Pittsburgh Press.
Lelas, S. (1993). Science as technology. *The British Journal for the Philosophy of Science, 44*(3), 423-442.
Lindwall, O. (2008). *Lab work in science education: Instruction, inscription, and the practical achievement of understanding*. Linköping: Linköping Studies in Arts and Science No. 426.
Lindwall, O., & Ivarsson, J. (2010). Differences that make a difference: Contrasting the local enactment of two technologies in a kinematics lab. In S. Ludvigsen, A. Lund, I. Rasmussen & R. Säljö (Eds.), *Learning across sites: New tools, infrastructures and practices*. Amsterdam: Elsevier.
Lunetta, V. N. (1998). The school science laboratory: Historical perspectives and contexts for contemporary teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (Vol. 1, pp. 249-262). Dordrecht: Kluwer.
Lunetta, V. N., Hofstein, A., & Clough, M. P. (2007). Learning and teaching in the school science laboratory. In S. Abell & N. Lederman (Eds.), *Handbook of research on science education* (pp. 393-441). Mahwah: Lawrence Erlbaum.
Marton, F., & Pang, M. F. (2008). The idea of phenomenography and the pedagogy of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 533-559). New York: Routledge.
Marton, F., & Tsui, A. B. M. (Eds.). (2004). *Classroom discourse and the space of learning*. Mahwaw: Lawrence Erlbaum.
Nardi, B. A., & Kaptelinin, V. (2006). *Acting with technology: Activity theory and interaction design*. Cambridge: MIT Pressi
Nemirovsky, R., Tierney, C., & Wright, T. (1998). Body motion and graphing. *Cognition and Instruction, 16*(2), 119-172.
Popper, K. R. (1972). *The logic of scientific discovery*. London: Hutchinson.
Psillos, D., & Niedderer, H. (Eds.). (2002). *Teaching and learning in the science laboratory*. Dordrecht: Kluwer.
Radder, H. (2003). Toward a more developed philosophy of scientific experimentation. In H. Radder (Ed.), *The philosophy of scientific experimentation* (pp. 1-18). Pittsburgh: University of Pittsburgh Press.
Selinger, E. (Ed.). (2006). *Postphenomenology: A critical companion to Ihde*. Albany: State University of New York Press.
Singer, S. R., Hilton, M. L., & Schweingruber, H. A. (Eds.). (2006). *National research council, committee on high school laboratories: Role and vision, America's lab report: Investigations in high school science*. Washington DC: The National Academies Press.
Sokoloff, D. R., Laws, P. W., & Thornton, R. K. (2007). RealTime Physics: Active learning labs transforming the introductory laboratory. *European Journal of Physics, 28*(3), S83-S94.
Still, A., & Costall, A. (1987). Introduction: In place of cognitivism. In A. Still & A. Costall (Eds.), *Cognitive psychology in question* (pp. 1-16). Brighton: Harvester Press.
Tala, S. (2009). Unified view of science and technology for education: Technoscience and technoscience education. *Science & Education, 18*(3), 275-298.
Tala, S. (in press). Enculturation into technoscience: Analysis of the views of novices and experts on modelling and learning in nanophysics. *Science & Education*, 1-28.
Thornton, R. K. (1996). Using large-scale classroom research to study student conceptual learning in mechanics and to develop new approaches to learning. In R. F. Tinker (Ed.), *Microcomputer-based labs: Educational research and standards* (pp. 89-114). Berlin: Springer.
Thornton, R. K. (1997). Learning physics concepts in the introductory course: Microcomputer-based labs and interactive lecture demonstrations. In J. Wilson (Ed.), *Proceedings conference on introductory physics course* (pp. 69-86). New York: Wiley.
Thornton, R. K. (2008). Effective learning environments for computer supported instruction in the physics classroom and laboratory. In M. Vicentini & E. Sassi (Eds.), *Connecting research in physics education with teacher education*: International Commission on Physics Education (ICPE).
Tiberghien, A. (1998). Labwork activity and learning physics - an approach based on modeling. In J. Leach & A. Paulsen (Eds.), *Practical work in science education* (pp. 176-194). Fredriksberg: Roskilde University Press.
Tinker, R. F. (Ed.). (1996). *Microcomputer-based labs: Educational research and standards*. Berlin: Springer.
Trumper, R. (2003). The physics laboratory: Historical overview and future perspectives. [10.1023/A:1025692409001]. *Science & Education, 12*(7), 645-670.
Whitehead, A. N. (1963). *Science and the modern world*. New York: New American Library.