Computational problem solving in university physics education
Students’ beliefs, knowledge, and motivation

Madelen Bodin
To my family
Thanks

It has been an exciting journey during these years as a PhD student in physics education research. I started this journey as a physicist and I am grateful that I’ve had the privilege to gain insight into the fascination field of how, why, and when people learn. There are many people that have been involved during this journey and contributed with support, encouragements, criticism, laughs, inspiration, and love.

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List of papers

The thesis is based on the following papers.


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1 Introduction

Physics education research is research about how we learn, teach, understand, and use physics. The fundamental research questions are intriguing as they address how human intelligence relates to the laws of nature and how we explain the world around us. As an applied science, physics education research has the prospect of improving teaching and learning in terms of new tools and methods. Physics education research is an interdisciplinary research area and combines two fields with different research traditions. Education research is influenced by, e.g., social studies, psychology, and neuroscience. Physics is a traditional academic subject but is also integrated in a number of other fields such as chemistry, biology, computer science, and even economy and sociology. Physics education research can therefore be approached in many ways depending on the particular questions asked and the context chosen for the research, as well as find applications outside physics.

1.1 Aim of the thesis

The teaching and learning situation in focus in this thesis moves across the fields of physics, mathematics, computer science, and the problem solving associated with these fields. It is situated in a university context and the assignment in focus is a physics problem in classical mechanics where students use computational physics to develop a simulation.

This work strives at contributing to understanding of the cognitive and affective learning experiences from a computational physics assignment where competencies from several fields interact. The assignment is thus not limited to finding a sole physics solution but includes numerics, computer science, as well as visualization and interactivity. Will this complex situation help or hinder the student from developing a coherent view of how physics is used to model and understand the world? The overall research questions treated in this thesis are:

- What are the critical aspects of using computational problem solving in physics education?

- How do teachers and students frame a learning situation in computational physics? Do teachers and students agree about learning objectives, approaches, and difficulties?
What are the consequences in terms of positive or negative learning experiences when using computational problem solving in physics education?

My aim with this thesis is to contribute to the metacognitive understanding of how students learn computational physics and to provide university teachers with knowledge about effects of using computational thinking in university physics education.

1.2 Context of the study

The context for this thesis is physics education at university level. Studying physics at university level can have several purposes. A physics student can aim at becoming a scientist and therefore chooses a traditional physics education. Another student may have a different career in mind and chooses an engineering approach of physics studies. A third student is interested in becoming a schoolteacher and chooses to study physics where the pedagogical aspects in combination with physics play important roles. The motivation to study physics may differ in these three exemplified cases but the understanding of physics as a subject should not differ (Heuvelen, 1991). The academic physics education is often concentrated on learning physics concepts, solving physics problems, and using physics principles in order to explain phenomena and predict physical processes (McDermott, 2001; Redish, 1999). The engineering approach tends to focus more on methods and tools for solving physics problems as emphasize may be directed towards constructing technology and finding solutions to technological and scientific issues (Redish, Saul, & Steinberg, 1998). The teacher student is, on the other hand, besides learning the physics subject, interested in metacognitive aspects such as, how physics is learned, what students have difficulties with, and how the teacher's knowledge can be implemented in a classroom situation (Arons, 1997). Studying these different approaches and interests in learning and teaching physics all contribute to knowledge about how students learn physics and how teaching can be improved.

The term computational scientific thinking has been used in a number of contexts during the past years as a way to approach science that would not be available otherwise (Landau, 2008). Ken Wilson proposed computation to be the third leg of science, together with theory and experiment, due to breakthroughs in science because of new computational models, findings that actually awarded Wilson a Nobel prize in 1975 (Denning, 2009). Approaching science with a computational mind would therefore be expected to be present in tertiary physics education but this is generally not the case, even though several initiatives have been taken in this direction (Johnston, 2006; Landau, 2006).
The following definition of computational physics was proposed by the editor in chief of Computing in Science and Engineering, Norman Chonacky in relation to a, in the U.S., nation-wide survey among teachers about how computational approaches were used in undergraduate physics education:

"By computation in physics here we mean uses of computing that are intimately connected with content and not its presentation. There seems to be no concurrence on which role(s) are appropriate for computing in physics, but there is a distinction we can draw between computers used for instructional methodologies and computers used for computational physics. We’re interested in the latter where, as in calculus, we use computation to derive solutions to problems." (Fuller, 2006)

Using computation in physics education is not a new approach. Numerical methods have for long been important resources in solving complex physics problems. However, without resources such as computers and numerical methods, calculating numerical solutions is a very time-consuming business. In recent years the interest in the field of implementing computational physics in conventional physics education has increased in the physics education community and some of these reasons are:

- The accessibility to computers in education has increased. Computers are becoming a natural tool in education and most students already use computers in their everyday life (Botet & Trizac, 2005).

- Increasing computer capacity gives possibilities to graphical and computational challenges. Computer processors are getting more and more powerful and computations as well as rendering of graphics in real time open up for technologies for visualization of physics (Johnston, 2006).

- Problem solving and simulation environments open up possibilities to work with realistic problems. Software together with increasing computer capacity give even more possibilities to approach realistic physics problems, problems that are not possible to solve without using numerical methods and computers (Chabay & Sherwood, 2008).

- Computation has in recent years been considered as important as theory and experiments in science and would therefore be expected to be represented on the same terms in education (Landau, 2006).
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Competence in computational physics gives access to new types of jobs in emerging industries that often are considered attractive and motivating to students, e.g. in movie visual effects, computer games development, interaction technology, and computational design (Denning, 2009).

Computers in physics education thus seem to offer extensive possibilities to investigate physical phenomena as well as solving realistic problems. However, what will the students actually learn? Is solving complex problems with computational physics a way to gain knowledge in physics or is physics learning hindered by learning other competencies such as programming and numerical modeling of physics? Figure 1 illustrates how this increased complexity adds another dimension to traditional problem solving skills in physics, math, and modeling.

My purpose with this thesis is to investigate cognitive and affective aspects related to students' and teachers' experience with computation and simulation in physics education. There is a huge difference in student activity between developing a simulation and using a simulation. I have focused on the situation in which students with computational approaches develop a visual interactive simulation as a solution to a physics problem.
1.3 Overview of the thesis

This thesis comprises an introductory section and four papers.

Chapter 2 consists of a background to learning and teaching physics. This deals with characteristics of physics as a subject and presents previous research on teaching and learning physics. This gives an ontology, i.e., a description of what is out there to know and how I decide what questions that are of interest.

In the conceptual framework, chapter 3, the issues concerning my epistemological views of teaching and learning physics are treated, i.e., what can we know about this field and how can we know that. This part deals with how knowledge can be represented, the influence of personal beliefs and attitudes on learning, and what role motivation plays in learning.

The research questions investigated in the four papers in this thesis are presented in chapter 4 and they are further covered in the four accompanying research articles.

In the methodological framework in chapter 5 issues concerning methods are described. Methodology deals with the precise procedures that can be used to acquire the knowledge necessary to answer the research questions, i.e., what data and how it should be collected and how the data should be analyzed. In the methodological framework I describe and discuss the methods for data collection and analysis and their relevance for answering the research questions.

The results from the studies are presented as a summary of the four papers in chapter 6.

In chapter 7 the main findings are summarized and discussed and chapter 8 concludes the thesis.
2 Learning and teaching physics

In this chapter and the following, chapter 3, I describe what my choice of research questions is based upon. This thesis is not only about teaching and learning physics but also about applying knowledge and skills from several disciplines in order to solve and simulate a realistic physics problem using computational methods. The questions in focus deal with what can be learned from the students' experiences in terms of cognitive and affective aspects.

2.1 Why learning physics?

Physics is a unique subject since it involves many levels of abstractions in different forms of representations, e.g., conceptual (laws, principles), mathematical formalism (equations), experimental (equipment, skills), descriptive (text, tables, graphs) (Roth, 1995). Hence, what it actually means to understand physics is a challenging question. Knowing a phenomenon's causes, effects, and how to interact with it are some of the attributes related to understanding (Greca & Moreira, 2000) which also fit the purposes of learning physics.

Physics is formulated in order to try to explain the world we live in. Therefore we have invented physics as a tool in order to gain knowledge about our environment and ourselves. Brody (1993) refers to physics as an epistemic cycle where physics is not a finished product but is instead the process of creating that product, physics itself. This is expected to give physics knowledge a particular epistemological touch (Roth & Roychoudhury, 1994) where knowledge about physics can lead to knowledge about how and why we learn. Humans are fit to handle the physical conditions that the world provides, such as space, time, and mass. Our bodies have generally no problem to act in this world, but when it comes to formulating and communicating what we experience, our brains seem to be less comfortable. Classical mechanics is what our bodies most easily can experience and observe, and thus what is easiest to collect empirical data about. Some of the most fundamental aspects of physics, such as energy and momentum conservation and Newton's laws of motion, are based on empiricism from classical mechanics, and therefore have a position as fundamental for all physics. In physics education we generally start to learn mechanics in order to practice how to model what we experience before we move to more abstract phenomena, such as electricity, magnetism, and quantum mechanics.

Physics education research has a long tradition and is mainly associated with the traditional learning motifs, approaching physics concepts,
principles, and problem solving with the purpose of learning conceptual physics and solving analytical problems. Much of the focus is also devoted to finding answers to how novice students can develop the type of intuitive knowledge that expertise in the field seems to possess (Chi, Feltovich, & Glaser, 1981; Larkin, McDermott, Simon, & Simon, 1980). Results so far show that in general there are no short cuts, but there do exist better or worse ways of learning physics (Redish, 1999). An active engagement in learning, rather than passive reception, has for long been promoted to stimulate the cognitive development according to constructivist views on learning as well as motivational aspects (Benware & Deci, 1984; Heuvelen, 1991; McDermott, 2001; Prince, 2004). To actively engage in the physics studies, e.g., discuss problem solving strategies in groups, or to work with interactive computer environments for investigating phenomena or solving problems, usually promote a more coherent view of physics (Redish & Steinberg, 1999) (Laws, 1997) (Evans & Gibbons, 2007) while passive learning, e.g., listening to lectures and means-ends problem solving, tend to leave the student with physics as consisting of isolated facts (Reif, 1995) (Halloun & Hestenes, 1998).

### 2.2 Problem solving in physics

The main activity in practicing physics is to solve problems. I will here refer to any question that regards physics to be seen as a physics problem, which can be solved by using observations, mathematics, and modeling. If the problem is simple, an observation can be enough to find an answer. If the problem is complex, we might need numerical methods to simulate the problem and provide visualizations we can interact with to find solutions and answers.

Problem solving in physics education is a vast area of research and covers many aspects of how students as well as teachers experience problem solving in the learning and teaching process as shown, for example, in the review by Hsu, Brewe, Foster, and Harper (2004). The meaning of a physics problem is very broad and can be anything on the continuum from a closed problem, with a unique mathematical solution, to an open problem, which has no single answer and which can have several solutions. In physics education, traditional textbooks usually offer physics problems that are reduced to an idealized context and illustrate a single physics principle. The purpose is to train students to be familiar with physics principles and the corresponding mathematical formalism. These problems are typically quantitative, focusing on finding appropriate formulas and manipulating the equations to solve for a numerical value, i.e., encouraging a means-ends strategy. Previous studies have shown that problems where means-ends strategies can be used, can usually be solved without applying any conceptual understanding of physics.
principles (Larkin et al., 1980; Sabella & Redish, 2007). Being able to mathematically manipulate equations is indeed one aspect of being proficient in physics problem solving. However, students also need to model and solve open and more complex problems in order to develop expert-like problem solving skills as well as to achieve a coherent knowledge in physics (Hestenes, 1992; McDermott, 1991; Redish & Steinberg, 1999).

2.2.1 Observations

Before a problem can be solved there need to be some sort of data. We need to know something about the context of the problem. This data can be provided by observations, for example the type of information that is given in a physics problem about velocity, mass, etc. Observational data can also be obtained by conducting a systematic experiment. Data can also be represented by known quantities, e.g., that the problem is set on earth, which means that we know or can easily find the gravitational acceleration or the distance to the center of earth.

2.2.2 Physics principles

When solving a physics problem there are a number of physics principles that can be applied in order to model the problem or to check whether the solution is reasonable or not. These physics principles are based on empirical data, discussed, and developed within the physics community for many years and considered to be general in the physical systems they represent. Some principles are considered as scientific laws of nature, which represent theories that describe nature. Some examples are Newton’s laws of motion and the conservation laws, e.g., energy, momentum, and electric charge. A law within physics does not claim to hold the truth. It is simply the best agreement that the model expressed by the law is a very good description and has not yet been proven to not be valid. For example, Newton laws of motion are regarded as excellent when explaining our macroscopic world but they do not explain effects arising in the microscopic world where quantum effects have to be considered. Research on student epistemologies, however, show that novice students often comprehend physics principles as the truth, believing that knowledge is something that is possessed by authority (Hammer, 1994). Physics principles are necessary tools for problem solving but it is also important to understand their origin in order to know how to model physics.
2.2.3 Mathematics

Mathematics is the language we use to understand and communicate physics as well as other sciences. Most physics students need some mathematics experience prior to studying physics. However, mathematics in physics seems to differ from mathematics in math courses (Bing & Redish, 2009; Martínez-Torregrosa, López-Gay, & Gras-Martí, 2006; Redish, 2005). Mathematics used in physics is applied, focusing on using mathematical methods, e.g. differential equations and vector analysis, with physics principles, in contrast to mathematics courses where abstractions and proofs play larger roles. This causes trouble among students who are unable to transfer their mathematical knowledge into the applied context that physics comprises. This is reported in several studies among tertiary physics students. Students have been found to have trouble, even after one semester of calculus, expressing physics relationships algebraically (Clement, Lochhead, & Monk, 1981) and to lack knowledge of concepts such as "derivative" and "integration" (Breitenberger, 1992). Bing and Redish (2009) studied different ways of how students frame the use of mathematics in physics. They found that even though students had knowledge and skills of how to apply certain mathematics in order to solve a problem, they often got stuck in a frame that would not lead them right. If, for example, students failed to solve a problem due to the wrong mathematical approach, they were unable to map the physics to the appropriate math without assistance. Knowing how to use mathematics in physics is therefore an important issue in order to be proficient in physics problem solving.

2.2.4 Modeling

Modeling plays a central role in science. Modeling is about constructing models that can describe and predict a phenomenon or a process. Solving a physics problem includes knowledge about physics principles relevant for the task and the mathematical formulations needed for the computations. Depending on the complexity of the physics problem it is often necessary to simplify the model in order to be able to calculate a solution. Typical simplifications that are made are omission of air resistance when modeling an object thrown through the air, or to consider the raindrop as spherical when modeling the rainbow. This might cause discrepancies between the student's personal experiences and what the model describes. To understand what properties that can be neglected and when and what has to apply, such as a certain physics principle, requires fundamental understanding of the physics principles as well as how to apply the mathematical methods. Hestenes (1987, 1992) suggests that physics should be taught with a modeling approach in order to train students to use physics principles and
Learning and teaching physics

mathematical methods from the beginning. This would help student to learn more efficiently and develop a more coherent view of physics. Other studies support modeling as an epistemological framework for teaching, both using the *model* to teach the content of physics and the *modeling* activity to teach scientific knowledge and procedures (Etkina, Warren, & Gentile, 2006; Greca & Moreira, 2002; Halloun, 1996).

**2.2.5 Computational physics**

With computational methods other dimensions of physics problem solving can be reached and complex problems can be available for solving that would not be possible to solve using only paper and pen. This typically means realistic problems with many interacting objects. An example of a physics problem that requires computational methods and is central in this thesis is how to model an elastic macroscopic object sliding over a rough surface; how can the friction coefficient be determined? This problem requires a physical model for the object as well as the ground, numerical methods that calculate all relevant force interactions using appropriate time steps, and physics principles, such as energy and momentum conservation.

Skills in computational thinking means to be able to give structure to calculations, i.e., to organize the mathematical operations that are needed to solve a numerical problem. Computational methods are everyday tools for physicists and engineers. Still many physics educators hesitate to use computational approaches when teaching physics (Fuller, 2006). Numerics are usually provided as numerics courses rather than integrated in physics courses. Previous research has shown that students have problems integrating mathematics into the physics context because students are not able to transfer knowledge between the contexts of mathematics and physics courses (Bing & Redish, 2009; Redish, 2005). The same effect could therefore be expected when students are exposed to numerical methods in physics courses. A computation approach to problem solving does not only require knowledge about how to use a chosen numerical method together with the physics but also how to tell the computer to do the calculations, i.e., to program the computer. This provides a complex situation for a physics student, having to deal with many competencies, which might obstruct elaboration of physics knowledge. However, with computational methods complex and realistic physics problems can be exposed to students. A computational physics problem, e.g., simulating force interactions between many particles, is seldom possible to solve using only a means-ends strategy, and is thus a type of problem that is suitable for a modeling approach in teaching. However, the importance of designing activities is discussed in several studies. Buffler, Pillay, Lubben, and Fearick (2008) suggested a framework for designing computational problems for physics students based
on feedback on students mathematical models prior to programming in order to facilitate for students to focus on the physics. Cabellero (2011) designed and tested a computational assignment in classical mechanics and identified some common students mistakes in three categories: initial condition errors, force calculation errors, and errors with Newton's second law. This leads to suggestions for adding additional material to the assignment but also on focusing instructional effort on qualitative analysis of solutions. There are few studies on students’ cognitive or affective experiences of solving physics problems with computational approaches. Therefore the studies conveyed within this thesis and the corresponding results fill a knowledge gap about these learning situations.

2.2.6 Simulations

Computational physics has the purpose of simulating the problem that is investigated. Simulations are theoretical experiments and provide insight into computational models of physics systems, which can be manipulated and interacted with in order to explain their properties. A simulation is often represented by a visualization of the computed data. Using computers and simulations in physics education has been subject of several studies with different approaches. Monaghan and Clement (1999) proposed that using computer simulations can facilitate students' own mental simulation in order to form a framework for visualization and problem solving. Another approach was made by Vreman de Olde and de Jong (2004) in which students were stimulated into a more active learning mode by letting them create assignments for each other on electrical circuits in a computer simulation environment.

When simulations are mentioned in the same sentence as physics education it can mean different things. Environments for computational physics and simulations may differ significantly with regard to the learning conditions they provide, representing different levels of autonomy and requiring more or less knowledge and skills in modeling, programming, mathematics, or conceptual physics. Questions have been raised whether simulation activities actually help students learn physics (Steinberg, 2000). A simulation environment does not necessarily provide active engagement of the learner. Many simulation environments that are supposed to engage students and help them develop their schemata for physical problem solving, are rather functioning as passive learning environments offering small opportunities for students to actually participate in the simulation process. I will here differ between three ways of working with simulations in physics education: using pre-made simulations (or animations), using simulations as tools, and building simulations.
Students can use simulations to illustrate a phenomenon. An animation can also illustrate a phenomenon but where the animation rather is an artistic illustration, the simulation is based on computation of the equations of physics. An animation does not offer any possibilities to interactivity. A simulation, however, illuminates certain aspects of the physics involved in the phenomenon and offers interactivity, e.g., to change parameters in order to investigate what happens under other conditions. Simulation applets like PhET (Perkins et al., 2006) or many of the applets that can be found on the internet may provide interactivity in terms of possibilities to change parameters and investigate different phenomena but do not require any computational skills.

Students can use simulations as tools to solve problems. In this case we have a simulation environment that is used for declaring systems for investigation and testing of models within the physics that is covered by the simulation environment. This situation does not generally need knowledge about the physical and numerical models. An example of a simulation tool is Algodoo (Bodin, Bodin, Ernerfelt, & Persson, 2011), which provides a graphical interface but uses advanced numerical solvers for calculating physics interactions.

Students can build simulations using different problem solving environments and tools. This can span from programming the physics and math to visualize a phenomenon to using simulation environments with built-in physics- and math-engines. Pure programming environments, such as C++ and Java, are common among scientists and provide a very open approach to numerical problem solving of physics. Maple, Mathematica, Matlab, and Octave provide some support in terms of functions and graphics but do require a computational thinking approach (Chonacky & Winch, 2005). Easy Java Simulations (Christian & Esquembre, 2007) and VPython (Chabay & Sherwood, 2008) are environments which provide support in computation as well as visualization through physics engines and visualization libraries.

To use simulations can provide visual representations of complex phenomena and help students develop their conceptual understanding. To build simulations is expected to require a more active participation from the student giving possibilities to actually model and control physical systems. These different types of simulation environments are therefore believed to provide different learning outcomes. The point of interest in this work is to study a situation where the student is given as much control over the simulation as possible. In order to stimulate the acquisition of expert-like
cognitive structures for problem solving, this approach is expected to provide positive learning outcomes.

The difference between a simulation and a visualization is not straightforward in many cases. The result from a simulation is usually a visualization but visualizations can also be provided as fictive animations. Scientific visualization is a competence and research area in itself, both in terms of developing visualizations and to interpret visual representations (Hansen & Johnson, 2005). Many agree that visualizations should have a central role in science education as well (Gilbert, 2005). Humans have an excellent memory for visual information and tend to remember a particular visualization’s meaning rather than the actual visualization (J. R. Anderson, 2004; Crilly, Blackwell, & Clarkson, 2006). Visual representations of data are invaluable when it comes to, e.g., interpret the data generated from a computational model (Naps et al., 2002). However, visualizations are expected to provide, as for simulations, different learning outcomes depending on how they are used in physics education. Tools for animation and simulation together with the Internet have made visualizations of physics phenomena accessible to every teacher and student, both in terms of studying visualizations and creating visualizations. In this work I refer to visualization as the visual feedback that is generated to the students as they build their simulations.
3 Conceptual framework

In this chapter I present the underlying background that I have used in order to investigate the research question. More details on the framework concerning the specific studies are provided in Papers I - IV.

3.1 Knowledge representation

Knowledge itself exists in many forms in the research literature. Alexander et al. (1991) provided a summary of up to thirty different types of knowledge constructs that have previously been used in research and to this list several more can be added. When knowledge is referred to in education it is often in terms of using and creating knowledge and skills associated with a subject. Common categorizations are conceptual, procedural, and metacognitive knowledge (J. R. Anderson, 2004; de Jong & Ferguson-Hessler, 1996; Jonassen, 2009). This is also how I will refer to knowledge.

There are many ways of describing an individual's complex thinking in and about physics and learning physics in terms of cognition. The term cognition refers to the mental processes associated with, e.g., remembering, solving problems, and making decisions. The general consensus among cognitive scientists, psychologists, and neuroscientists is that understanding happens when knowledge components interact and form structures (J. R. Anderson, 2004). These knowledge components can have different properties (Merrill, 2000), levels (Grayson, Anderson, & Crossley, 2001), distinctions in meaning (L. W. Anderson & Krathwohl, 2001), and how they are used (Novak, 2010), but they are linked by the underlying idea of knowledge as represented by knowledge components that are connected in some pattern.

The common components in cognitive frameworks for learning and memory form a knowledge base consisting of declarative and procedural knowledge, i.e., concepts forming a vocabulary for the field in order to communicate and procedures for applying the knowledge (J. R. Anderson, 2004). Also metacognitive components, such as beliefs, are considered to play important roles (Flavell, 1979; Kuhn, 2000). One frequently used framework for learning is Bloom's revised framework, which apply these different types of knowledge, described below, to different cognitive processes, from remembering facts to generating new knowledge (L. W. Anderson & Krathwohl, 2001).

**Concepts - conceptual knowledge.** To possess conceptual knowledge is to understand what the conceptual vocabulary means, i.e., to understand the meaning of physics concepts and how they are connected to form physics principles. Novice students often possess alternative conceptions, i.e., have
adapted ideas of how physics concepts are related that are not consistent with the laws of physics, e.g., an object in motion requires a force acting on the object, or that electric charges are consumed in an electric circuit (Dykstra, Boyle, & Monarch, 1992; Slotta, Chi, & Joram, 1995).

**Actions - procedural knowledge.** Procedural knowledge in physics means to know how to do in order to solve a physics problem. This includes strategies, methods, and tools for modeling, problem solving, and computations in order to solve a problem (Hestenes, 1987).

**Beliefs - metacognitive knowledge.** Metacognitive knowledge refers to knowledge about the learning process, both in general terms and one's own learning process (Veenman, Hout-Wolters, & Afflerbach, 2006). A common construct that captures metacognitive aspects of learning is beliefs. I here distinguish between two types of beliefs that I have found useful in order to explain the background to my work; epistemological beliefs relating to knowledge and learning (Hofer & Pintrich, 2002), and value beliefs, which captures attitudes and reasons for engaging in activities (Eccles & Wigfield, 2002). Beliefs are further considered in section 3.5.

### 3.2 Structures in knowledge

The organization of knowledge is described in several ways in the literature about physics education research. Schemas (Chi et al., 1981), scripts (Redish, 2004), mental models (Corpuz & Rebello, 2011; Greca & Moreira, 2000; Larkin, 1983), and frames (Elby & Hammer, 2010; Hammer, Elby, Scherr, & Redish, 2005) are some of the constructs that are used in order to describe how physics knowledge is internally represented in the human mind. What follows is a short description of the differences between these constructs and how they have been used in previous research in order to investigate memory, understanding, and learning.

**Schemas** are formed by chunks of knowledge organized in an associative pattern that are activated by a stimuli (Chi et al., 1981; Derry, 1996; Redish, 2004). Schemata facilitate both encoding and retrieval of information and is based on the assumption that what we remember is related to what we already know (J. R. Anderson, 2004). Schemas correspond to an active process depending on new experiences and learning. Schemas can also be seen as run schedules (event schemas) that are activated by particular tasks or situations and are sometimes referred to as **scripts** (Schank & Abelson, 1977).

**Mental models.** According to Johnson-Laird (Johnson-Laird, 1983), mental models are personal constructions of situations in the real world that we can use, test, and mentally manipulate to understand, explain, and predict phenomena. Mental models can be seen as internalized, organized knowledge structures, representing spatial, temporal, and causal
relationships of a concept, that are used to solve problems (Rapp, 2005). Mental models are actually never complete, but constructed as understanding of, e.g., a physics phenomenon, and correspond to abstract representations of memory. Thus mental models can be seen as working models for comprehension of different situations. Investigating mental models in education research is expected to give information of the type of memory that students build in different learning situations. This information can be used to suggest circumstances in teaching and learning under which accurate mental models can be constructed. However, mental models rely on a person’s individual understanding and beliefs, and do therefore not always correspond to a valid or reliable representation (Rapp, 2005).

Due to the abstract character of mental models and their ability to change over time they are difficult to define. Carley and Palmquist (1992) addressed a number of issues in order to develop methods for assessing mental models. Mental models are internal representations held by the individual in contrast to external representations such as concept models or mathematical models (Greca & Moreira, 2002). An important issue concerns language as being the key to mental models, i.e., mental models can be represented by words. Mental models are also assumed to be represented as networks of concepts and the meaning of a concept for an individual lies in its relations to other concepts in the individual’s mental model.

**Framing** corresponds to an intuitive reaction when exposed to some kind of activity and deals with the question “What is going on here?” The construct has previously been used in linguistics, cognitive psychology, and anthropology. Tannen and Wallat (1993) defined framing in terms of individual reasoning and summarized the concept of frame as the set of expectations, based on previous experience, an individual has about a given situation or, widely spoken, a community of practice. Minsky (1975) used frame as describing the cognitive structure that a person recalls (memory) when entering a new situation, e.g. a learning situation. When a person enters the situation a frame that represents a previous situation is loaded. If the frame doesn’t fit, it is replaced or revised until it fits the situation. In an educational setting, a student's framing used for interpreting a learning situation can be expected to be based on cognitive and context-specific experiences concerning, e.g., prior knowledge, skills, and beliefs, but also social aspects, such as relations to other people, and on what resources that are available for learning, such as literature and teachers. Due to the particular context of a learning situation that is recalled in this thesis I have chosen to call these building blocks involved in creating knowledge *epistemic elements* and consequently *epistemic framing* is chosen to describe the organization of these epistemic elements. Epistemic or epistemological framing have previously been used in research when investigating students'
expectations (Bing & Redish, 2009; Elby & Hammer, 2010; Scherr & Hammer, 2009; Shaffer, 2006).

Networks can be used to represent the relations between knowledge components. The knowledge components are referred to as nodes and the links between them as edges. A common representation is the semantic network that encodes the structure of conceptual knowledge (Hartley & Barnden, 1997).

Several studies have applied networks as representations of knowledge. Shavelson (1972) employed a network approach to investigate the structure of content of an exercise in relation to cognition after a teacher intervention in the context of classical mechanics using the number of connections between specific concepts as evidence of learning. In a study about digital learning environments Shaffer et al. (2009) visualized epistemic frames using an epistemic network analysis approach where the components consisted of knowledge as well as beliefs, giving a time-resolved development of students' epistemic framing. Jonassen and Henning (1996) assumed that semantic adjacency between concepts in a text could be approximated by geometric space and that cognitive structures could be modeled through semantic networks based on geometric adjacency. Carley (1997) proposed networks as representations of conceptual structures and developed a toolkit for building and analyzing networks as representations of mental models in different contexts (Carley & Palmquist, 1992). Koponen and Pehkonen (2010) investigated structures of experts' and novices' physics knowledge using concept networks comprising concepts, laws, and principles as nodes, and procedures, such as modeling and experiments, as edges, resulting in networks that can be used to interpret coherence in physics knowledge. Also concept maps are forms of networks linking knowledge components by their associative and causal meaning (Novak, 2010).

3.3 Concepts and meaning

Knowledge about a subject can be investigated by studying the language associated with that subject (Alexander et al., 1991). Language is, in the research done in these studies, assumed to be the key to students’ minds. What they experience and learn is expressed in their own words. According to Vygotskiï and Kozulin (1986), language is assumed to mediate thought and this assumption is used in order to represent students' mental models and epistemic frames as networks, using the concepts they express and how they interact. Noble (1963) suggested that the meaningfulness of a word was proportional to the number of its associates. When students acquire conceptual knowledge in physics, concepts would increase its associations
and thus increase their meaningfulness. The concepts students use and how they use them in relation to other concepts can thus be a measure of their conceptual knowledge (Brookes & Etkina, 2009; Koponen & Pehkonen, 2010; McBride, Zollman, & Rebello, 2010).

3.4 Visual representations

Previous research has shown that visualizations can help students build mental models for comprehension but visualizations by themselves do not necessarily lead to enhanced learning (Rapp, 2005). An interactive visualization is expected to stimulate cognitive engagement and an important feature would be to which degree a student can take control and interact with the visualization to study characteristics of a problem solution.

In a study by Monaghan and Clement (2000) it was shown that students who interacted with a visual simulation used mental imagery to solve the problem while students who only were exposed to numeric interventions of the same simulation used mechanical algorithms dominated by numeric procession. The authors suggested that with a combination of numeric and visual feedback, students would, in the ideal situation, integrate their numeric and visual representation to provide a coherent model of the problem.

3.5 Beliefs

3.5.1 Epistemological beliefs

Students’ beliefs about learning have in previous research been shown to be an important actor in the learning process of physics (Adams et al., 2006; Buehl & Alexander, 2005; Hammer, 1994; Schommer, 1993). In the context of introductory physics, Hammer (1994) used a framework consisting of three dimensions; structure of physics, content of physics knowledge, and learning physics when characterizing students’ epistemological beliefs. Student beliefs were found to influence students' work in the course and were also consistent across physics content. Hammer found, for example, that if students believed that physics knowledge consisted of facts rather than general principles, it was reflected in how these students solved problems and explained phenomena, relating to isolated facts rather than using physics laws and principles. Students' choice of strategies in order to solve a physics problem was also expected to be influenced by their beliefs about problem solving. Students might have problems facing a more open-ended, ill-structured task since the problem solving strategies generally taught in physics problem solving represent means-ends strategies, i.e., searching for equations that contains the same variables for the known and unknown
information in the task. Students need to believe that standardized equation matching is not always sufficient for solving engineering and scientific problems (Ogilvie, 2009).

### 3.5.2 Expectancy and value beliefs

Previous research on motivation in learning has also put emphasis on the importance of student beliefs. The expectancy-value framework is an important contribution to research on motivation in learning in order to predict academic achievement and holds expectancy beliefs and value beliefs as the two most important variables in achievement behavior (Eccles & Wigfield, 2002). Expectancy beliefs in terms of self-perceptions of competence have shown to be strong predictors of performance (Eccles & Wigfield, 2002) as well as cognitive engagement and learning strategies (Pintrich, Marx, & Boyle, 1993). Value beliefs refer to the reasons the student may have for engaging in a task, such as interest, value, and do mainly affect choice behavior and predict, for example, what courses the student will enroll in. (Eccles & Wigfield, 2002)

Students may also have beliefs about how to explain their achievement outcomes which has shown to be connected to beliefs about ability as well as value. Weiner (1992) found that the most important attributions for how the students performed in a task were ability, effort, task difficulty, and luck. For example, attributing ability to an outcome has stronger influence on expectancy of success, and thus actual performance, than attributing effort. Negative perceptions about own capability to complete the task, i.e., self-efficacy (Bandura, 1993), are strongly related to expectancy beliefs about failure (Eccles & Wigfield, 2002) and are expected be related to choices of less optimal strategies for learning.

### 3.6 Motivation

Motivation is what keeps us going when doing an activity, for example engaging in a learning activity. Motivation can vary in type as well as intensity (Ryan & Deci, 2000). The type of motivation has to do with the reasons for engaging in an activity, e.g., a student gets motivated to do an assignment because he or she gets paid, or by realizing the value of completing the assignment in terms of learning the skills needed for a profession. In self-determination theory (Ryan & Deci, 2000) the type of motivation is found on a intrinsic-extrinsic continuum where intrinsic motivation is described as a will to engage in an activity because it gives satisfaction, while extrinsic motivation is driven by a separable outcome. Ryan and Deci proposed that extrinsic motivation could vary and also consist of intrinsic aspects, depending on the degree of internalization and
integration of extrinsic goals. Intrinsic motivation exists within an individual and is, besides a self-determined behavior, manifested by positive emotions of enjoyment and satisfaction. The intrinsic character of extrinsic motivation is, due to internalization of goals, also experienced as self-determined behavior, leading to increased engagement and positive emotions and thus difficult to distinguish from true intrinsic motivation.

3.6.1 Autonomy

There are many perspectives on the role and origin of autonomy, i.e., self-determination, which is considered as an important variable in motivational frameworks (Ryan & Deci, 2000). Autonomy is a multidimensional construct and can take different forms depending on, e.g., stage of learning and context. It can be associated with the characteristics of a learning situation, e.g., how a task is designed in terms of the number of possible solution pathways and teacher support for autonomy, but also with characteristics of the learner herself, personal autonomy. A general description of personal autonomy is the learners’ possibility to take charge or control of their own learning (Benson, 2001). The level of responsibility for learning a student is capable of handling is thus expected to be dependent on the student’s knowledge and skills but also on epistemological beliefs, values, and goals associated with the task. Candy (1988) suggested that a learner’s autonomy in a given learning situation has two main dimensions: situational autonomy and epistemological autonomy. While situational autonomy is associated with independence from outside direction and the degree to which skills and knowledge are suited for the situation, epistemological autonomy is rather involved in the learner's ability to make judgments about the content to be learned and about strategies of inquiry. Littlewood (1996) argues for both ability and willingness as components for autonomy, where willingness in turn involves motivation as well as confidence (i.e., perceived ability) to work autonomously with a task. Willingness and ability can be seen as interdependent since the more knowledge and skills the student possesses, the more confident the student feels about working independently. Autonomy can be considered as being an important entity in the constructionist learning framework (Harel & Papert, 1991) where tasks are designed to motivate students to use their own knowledge in order to build things and thus create new knowledge. Autonomous behavior is encouraged by the guidance from teachers as well as the feedback from the results of their exercises, e.g., a computer simulation or a physical product, such as a building or a construction. Many problem-solving and simulation environments provide scope for autonomous behavior and are designed with a constructionist learning
approach in mind, e.g., Logo environment (Papert, 1993), Boxer (diSessa, 2000), SodaConstructor (Shaffer, 2006), and Algodoo (Bodin et al., 2011).

3.6.2 Indicators of motivation

The emotions that students experience in relation to a learning situation are often considered as good indicators of motivation in learning (Pekrun, 1992). According to self-determination theory (Ryan & Deci, 2000), intrinsic motivation generates positive emotions and indicate a will to engage in activity. Positive emotions, such as enjoyment or excitement, are also proposed to indicate a deeper cognitive engagement (Pekrun, Goetz, Titz, & Perry, 2002). Emotions expressing pleasure, control, and concentration are part of the flow framework (Csíkszentmihályi, 1990). Flow is described as an intense feeling of active well-being and is experienced when perceived skills and challenge of a task are above a threshold level and in balance. If flow is within reach, emotions like control and enjoyment function as activators that encourage the learner to increase their skills or the level of challenge to achieve balance. If the discrepancy between skills and challenge is too large, negative emotions like boredom, anxiety, uneasiness, or relaxation interrupts behavior, which might cause the learner to turn to another activity.

3.7 Experts, novices, and computational physics

University teachers in physics usually possess long-time experience within their fields. Their knowledge is often considered as tacit (Polanyi, 1967), i.e., not easily verbalized, automated and adapted as an expert level of knowledge (Dreyfus & Dreyfus, 1986). Tacit knowledge can also be related to the well-developed schema, or large chunks of interrelated physics principles and concepts, an expert activates when approaching a physics problem solving situation (Chi et al., 1981). A novice student can be considered to not yet possess appropriate schemas for physics problems and therefore has to rely on isolated facts and principles and a means-ends strategy for problem solving rather than a knowledge development strategy (Larkin et al., 1980). During a means-ends analysis of a problem there is a continuous evaluation between the problem state and the goal state. The focus lies on the quantity to be found and on trying to find expressions that connect that unknown quantity with the variables given in the problem, i.e., a formula-centered problem solving strategy (Larkin et al., 1980). In a knowledge development strategy, as is used in an expert sense, known information, e.g., physics principles, is used in order to develop new information, which leads towards the solution. A problem that can be solved using a means-ends strategy does not necessarily require any prior knowledge, just a set of actions, which in
the physics problem case means to search for equations that contains the unknown, e.g., as in the end-of-the-chapter physics problems described above. In order to avoid means-ends strategies for problem solving, Hestenes (1987) suggests that problem solving should be taught with a modeling approach, just as the expert approaches a problem by creating an abstract model of the given information in the problem statement and then develop the model in order to include also the unknown or searched information.

A computational physics problem, e.g., simulating force interactions between many particles, is seldom possible to solve using only a means-ends strategy, and is thus a type of problem that is suitable for a modeling approach in teaching. A numerical problem needs to be modeled, using not only appropriate physics principles, but also appropriate mathematical models as well as programming algorithms, and there is no unknown quantity to search for. Numerical problem solving in physics is therefore expected to force students to use an expert-like, knowledge development strategy in order to solve the problem. Solving complex problems also provides scope for autonomy and possibilities to be in control of the learning process, i.e., aspects of a learning situation that is considered as central in most motivational frameworks (Ryan & Deci, 2000).

Research shows that most students hold novice-like knowledge structures. Teachers need to be aware of possible misconceptions that students hold as well as their beliefs (Grayson, 2004). Many never develop expert-like physics knowledge and keep stating physics problems based on surface features instead of recognizing the physics principle that is applicable for the problem. In order to develop expert-like problem solving skills as well as to achieve a coherent physics knowledge students also need to solve open and more complex problems (McDermott, 1991; Redish & Steinberg, 1999).
4 Research questions

As discussed in the previous chapters there are many components that may affect learning in physics and the desired transition from novice towards expert. In this work I have the following research questions in focus:

- What are the critical aspects of using computational problem solving in physics education?

- How do teachers and students frame a learning situation in computational physics? Do teachers and students agree about learning objectives, approaches, and difficulties?

- What are the consequences in terms of positive or negative learning experiences when using computational problem solving in physics education?

In the papers these questions are developed and investigated as more specific questions:

- What are the relationships between students’ prior knowledge, epistemological and value beliefs, and emotional experiences (control, concentration, and pleasure) and how do they interact with the quality of performance in a learning situation with many degrees of freedom? (Paper I)

- What are the students focusing on, in terms of knowledge and beliefs, when describing a numerical problem-solving task, before and after doing the task? (Paper II)

- What role does physics knowledge take in describing a numerical problem-solving situation? (Paper II)

- When teachers say that something is important, how is this described in an epistemic network? (Paper III)

- How do students’ epistemic networks change between before and after the task? (Paper III)

- How do students’ and teachers’ epistemic networks differ? Are students and teachers focusing on the same critical aspects? (Paper III)
Research questions

- How do students’ mental models change during the assignment? (Paper IV)
- How do students programming code change during the assignment? (Paper IV)
- Are there any relations between progress in students’ mental models, the characteristics of the code, and the structure of the lab report? (Paper IV)

In addition to these educational research question I have introduced a, from an educational research perspective, novel method for extracting, investigating, and visualizing mental models, namely network modeling.
5 Methods

The empirical data used in the studies presented in this thesis originates from different data collection methods. Both fixed and flexible approaches are used in a mixed-method research design in order to carry out the investigations. Fixed research designs are typically well planned, e.g., an experiment or a survey, and could generate quantitative as well as qualitative data. A flexible design has room for development as the investigation continues, e.g., observations or interviews, and could also generate quantitative as well as qualitative data (Robson, 2002). Flexible designs are sometimes accused of being less scientific than the fixed design. However, scientific method, i.e., to consider systematics, objectivity, and ethics, must be the backbone of all research. The results are extracted using adequate methods of analysis, chosen due to their possibility of revealing patterns of interest in the collected data that correspond to the posed research questions.

5.1 The context of the study

The studies that form the basis for this thesis were carried out at the same university in Sweden. The same assignment in computational physics was used in all studies, except for the teacher interviews in Paper I and II. Three different student groups, from three different years, and four university teachers have contributed to the data.

5.1.1 The sample

The students participating in the studies were university students at their second year of their engineering physics education. Three different student groups, corresponding to a total of 87 students, from three consecutive years, contributed to the data sets. Students mean age was 22 at the time of the data collection. The students have contributed to the data set, either by responses to questionnaires, written lab reports, or as interviewees. There were only about 15% women and therefore no analysis concerning gender issues has been performed. Prior to the assignment subject for investigation, students had studied courses corresponding to mathematics 45 ECTS (European Credit Transfer System, where 60 ECTS corresponds to one year of full time studies), programming 7.5 ECTS, classical mechanics 9 ECTS, and numerical methods 4.5 ECTS.

In one of the studies, presented in Paper III, four university teachers from the departments of physics, math, and computer science contributed to the collected data.
5.1.2 The task

The instruction to the assignment subject for investigation is found in the Appendix. The assignment was part of a five-week course (7.5 ECTS) in mathematical modeling of physics. Prior to this assignment the course treated mathematical methods of physics in vector algebra. Students had also worked with a simulation environment for investigating electromagnetic phenomena.

Students were given about seven days of full time studies to complete the task, of which five days were teacher assisted computer lab time. This time is estimated due to the fact that the time for completing the assignment span over Christmas break giving about two weeks for holidays, which students could have used for self-studies. An intermediate deadline was set right before Christmas break in order to let the students turn in a preliminary report with a functioning simulation code to gain bonus marks for the examination of the course.

5.2 Data collection methods

The data collection methods were chosen based on what information that I wanted to retrieve in order to answer the research questions. I considered both quantitative and qualitative data to be necessary sources of information in order to cover the scope of the research questions.

5.2.1 Questionnaires

Questionnaires are commonly used for descriptive data about personal characteristics and their interrelations. A research questionnaire requires an extensive development design procedure based on the theoretical issues that are subject for the data collection to make sure the survey is measuring data that can be used to answer the research question (Robson, 2002).

Questionnaires were used in order to collect data that would provide information about students’ knowledge, beliefs, attitudes, and perceived emotions and mental effort in the learning situations forming the context of this research. Questionnaires were the main data collecting method in Paper I and used as complements in the other papers.

5.2.2 Interviews

Interviews were used to collect data in three of the articles. Interviews can be performed in many structural ways, from letting the interviewees respond to a questionnaire to letting them talk freely about anything. The interviews in this study have been semi-structured, meaning that for a particular set of
interviewees the same questions concerning a specific topic were posed to everyone and about the same time was allocated for every interview (Gillham, 2005). I performed all the interviews myself following interview guides that were prepared prior to the interview. All interviews were audio recorded and transcribed verbatim by me. Interviews were used in Papers II, III, and IV.

5.2.3 Students’ written reports and Matlab code

A third source of data used for investigation in this thesis was the students’ written reports from their assignment in computational physics. The reports consisted of a text where the answers to a number of questions posed in the lab instruction were supposed to be expressed in running text together with graphs and plots from the simulation. The students were also instructed to attach the Matlab code to their simulation. The purpose of using the lab reports as data was to collect information of students’ performance in the assignment and use this as a measure of their cognitive position after the assignment. Students’ written reports were used as data sources in two of the papers, Papers I and IV. In Paper IV the students’ Matlab code was also subject for analysis. Students were then asked to submit the Matlab code they had produced during each day during the assignment resulting in about five code samples from each student.

5.3 Analysis

Methods for analysis were chosen in order to extract the appropriate information from the collected data.

5.3.1 Multivariate statistical analysis

Multivariate statistical analysis involves statistical analysis of several variables collected at the same time in order to capture different aspects of a particular situation. A multivariate analysis approach gives information about how the variables are interacting in a specific situation and is also helpful in order to reduce a large number of variables. Projection methods are also adequate when there is noise in the data and when matrices have more variables than observations, which is common in small-scale studies like those presented in this thesis.

In this thesis questionnaire data has been subject for multivariate analysis in order to investigate interrelations between questionnaire items and to reduce the large number of variables that the questionnaires generated. The statistical methods used are the projection methods of principal component analysis (PCA) and its regression counterpart, partial least squares analysis.
Methods

(PLS) (Joliffe, 1986). The statistical software used for these analyses was Simca P12 (Umetrics, 2009). These methods are described more in detail in Paper I.

5.3.2 Content analysis

Analyzing textual data for educational purposes is usually done by a qualitative approach. I have used a mix of quantitative and qualitative analysis in order to extract meaning from the interview transcripts and the students' written reports. When I started to consider representing students' and teachers' knowledge and beliefs structures as visual networks I came across computer assisted methods of text mining and found that they could be useful in order to extract information from the interview transcripts. Semantic networks for content analysis as well as for knowledge representation have in previous research been proposed as useful tools (Atteveldt, 2008; Carley & Palmquist, 1992; Hartley & Barnden, 1997; Shavelson, 1972) and in order to prepare the data for a network analysis, textual preprocessing in terms of content analysis had to be performed.

Content analysis is often referred to as the methods of systematically studying the quantitative content of texts, e.g., frequency of certain concepts or length of utterances in a conversation (Robson, 2002). I have used content analysis in the wider meaning, including qualitative as well as quantitative aspects which is in line with the definition of content analysis as stated by Markoff, Shapiro, and Weitman (1975):

"Content Analysis [is] any methodological measurement applied to text for social science purposes. [...] the term refers to any systematic reduction of a flow of text, that is, recorded language, to a standard set of statistically manipulable symbols representing the presence, the intensity, or the frequency of some characteristics relevant to social science." (Markoff et al., 1975, p.5)

Also Krippendorff (2004) argues for content analysis as a tool for making inferences about the message context rather than just measuring aspects of the message content.

"Content analysis is a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use." (Krippendorff, 2004, p. 18)
Two applications of semantic network analysis have been used for content analysis in the studies presented in this thesis:

1. Coding of the textual data into *epistemic elements* using a qualitative analysis in order to meet the research questions followed by network analysis as a tool for visualization and further interpretation.

2. Computer-assisted text-mining of textual data into *context-dependent concepts* visualized as networks followed by a qualitative analysis in order to meet the research questions.

**Epistemic elements** are here statements expressing beliefs, knowledge or resources used in the learning situation. In the first method the interview transcripts were manually coded using a mix of confirmatory and exploratory approaches in order to find what epistemic elements that would constitute the networks. The confirmatory aspects meant that in order to categorize the meaning in the transcripts, statements expressing the principle categories of beliefs elements, knowledge elements, and resource elements, specific for the particular learning situation, were initially searched for. Beliefs were defined as statements expressing any opinion, goal, attitude, strategy, value, etc., that was associated with teaching and learning. Within the knowledge category any expression stating knowledge or skill about the sub-categories physics, math, programming, modeling, and problem solving, were registered as a knowledge element. The next step followed a more exploratory approach where elements within these principle categories were added as they were found to show relevance in the data set. These codes for epistemic elements were then replacing the actual expressions in the interviews, reducing the transcript to text document consisting only of codes for epistemic elements. These epistemic elements were then subject for network analysis, presented in the next section. This method of content analysis was used in the study presented in Paper I.

**Context-dependent concepts** are generalized words associated with the particular context. In the second method the textual data was preprocessed in order to reduce the text documents to consist of a limited number of context-dependent concepts that were explicitly describing the particular context of computational problem solving in physics education. These context-dependent concepts and their semantic relations would later constitute the networks. The text documents were initially run through a text-mining tool, Automap (Diesner & Carley, 2004). Automap is part of a toolkit for network analysis developed by Carley, Diesner, Reminga, and Tsvetovat (2007) and has functions for preprocessing texts, such as concept lists, delete lists, thesauri, as well as to generate networks. The textual data
were initially run through Automap in order to generate a union word list that covered all words that occurred in the entire text documents subject for analysis. The word list could be sorted alphabetically or according to frequency or relative frequency of words. This list was then manually treated in order to create a list of context-dependent concepts that could be used as a thesaurus for replacement of words into context-dependent concepts. Only words that had any meaning in the particular context were kept in the thesaurus. In questionable cases, e.g., words with multiple meanings, I consulted the original textual data in order to locate the words and determine their relevance. In order to further reduce the number of words, generalizations were made, e.g., words like simulations, simulate, and simulating were coded as "simulation". This procedure was repeated in an iterative process until the list of context-dependent elements were considered to still cover the meaning in the textual data but represent a manageable number of concepts. For every preprocessing action, i.e., replacing words with the context-dependent concepts, the transcripts were read through in order to make sure that meanings in the texts were kept intact. When all the replacements were done the text-documents were prepare for the next step of analysis, network analysis that would visualize the meaning in the textual data as networks of relations between context-dependent concepts.

This method was used in Paper III, where 26 concepts were considered to carry the meaning in the interview transcripts corresponding to the textual data, and Paper IV, where 101 concepts were used. Since the sets of concepts use in each study were strongly context dependent, it was necessary to generate a set of concepts for every situation depending on how fine-grained or general the analysis was planned to be. The smaller number of context-dependent concepts, used in Paper III gave a more coarse-grained base for further analysis, while more detailed information was kept in the study in Paper IV.

Comparison between the two approaches. Content analysis by coding the interview transcripts into epistemic elements corresponds to traditional qualitative analysis of textual data. It is a very time-consuming procedure but the information provided is rich and corresponds to elements representing the researchers knowledge base in the specific context. However, there is a limit to how much textual data that is possible to manually code. A computer-assisted text-mining approach is a fast way of determining the content of textual data and it is possible to analyze large amounts of data. There is however always difficulties associated with deciding which words that should constitute the set of concepts, especially when words have multiple meanings. To ensure reliability in this coding process it is desirable to return to the original textual data and double-check questionable cases. This is particularly important if only a few or small
samples are used. If large amounts of textual data is analyzed a few misinterpretations of concepts is expected to cause less noise.

By investigating occurrences of epistemic elements and context-dependent concepts in the reduced interview transcripts and lab reports information was revealed about what focus students and teachers had. In order to also investigate relations between these elements and concepts networks were built using elements and concepts as nodes and their semantic adjacency as links. This procedure is described in the next section.

5.3.3 Network analysis

Network modeling makes it possible to visualize and understand the complexity of a system with many interacting components or agents. Common applications of network modeling are, for example, social interactions, biological systems, information systems, and semantic patterns. Increasing computer capacity have made possible to investigate networks with billions of interacting agents, for example as in biological and computer networks. Studies of life systems and drug design are examples of applications of biological network analysis (Junker & Schreiber, 2008). Previous studies in network analysis are also associated with, e.g., social interactions (Wasserman & Faust, 1994), or semantic networks (Steyvers, 2005). In social network analysis the focus is on investigating relations between people in order to answer questions concerning economic, political, or social importance, for example, about terrorist networks (Borgatti, Mehra, Brass, & Labianca, 2009), or to understand the spreading of human diseases, e.g., SARS and the swine flu (Pastor-Satorras & Vespignani, 2001). Semantic networks represents the relation between concepts and can be used to represent knowledge within a context (Carley, 1997; Hartley & Barnden, 1997) as I will discuss further on in this section.

If a system is small, with only a few nodes and links, it can generally be visualized as is. Many systems, however, are very large and need to be described in a simplified manner. Depending on what information we want to draw from a network there are different methods of analysis. Investigating the formation of a network might require other methods than investigating the dynamics of a network. The formation of a network is often studied by a modularity approach where modules are formed according to higher density within the modules and a sparser structure between modules (Newman, 2006). For a system’s behavior, e.g., how local interactions between few nodes induce a flow through the whole system, it is interesting to understand the network’s dynamic structure and how the links regulate the flow. The map equation (Rosvall, Axelsson, & Bergstrom, 2009) is an information-theoretic algorithm which can optimize the path of a random walker in a network and describe how information flows in the network. Groups of
nodes cluster into modules where information flows quickly. The links between modules represent information paths, which connect the clusters and reveal the whole networks dynamic structure. In previous research the map equation has been used in networks to show the flow of information within the scientific community by studying cross citations of scientific journals (Rosvall & Bergstrom, 2008). The results revealed a bidirectional structure between basic sciences and a directed flow from applied sciences referring back to basic sciences giving information of how knowledge was flowing among scientists within different subject fields.

The choice of using network analysis as a tool for investigating students' and teachers' epistemic framings, conceptualizations, and mental models was based upon previous research about representing knowledge and beliefs as maps of concepts (Carley & Palmquist, 1992; Hartley & Barnden, 1997; Novak, 2010; Shaffer et al., 2009; Shavelson, 1972). The content analysis described in the previous section provided the epistemic elements and the context-dependent concepts that would form the node sets used for building the networks. In order to complete the networks the relation between the concepts were needed. Two approaches were used also here: 1) determining the relations between epistemic elements manually, as described in Paper II, and 2) generating the networks automatically based on adjacency between context-dependent concepts, an approach used in Paper III and IV.

**Manual building of networks.** In order to map students' epistemic framing the relations between the epistemic elements, described in the previous section about content analysis, were determined manually, a procedure described in detail in Paper II. The decision of a relation between two epistemic elements where mainly based on adjacency, i.e., elements that were close were linked in most cases, but also other connections between elements within a sentence or a paragraph could be considered as links. The weight of each link was equal to one and all links were bidirectional, i.e., I did not consider the direction of the link between two elements.

**Automatic generating of networks.** The second approach corresponded an automatic generation of networks. The tool Automap (Diesner & Carley, 2004), used for the text mining procedure used for coding textual data into context-dependent concepts, was used also here in order to generate semantic networks from the coded text documents. These networks were based only on adjacency between concepts, using a window of two, i.e., only elements that were adjacent were links. The unit of analysis was chosen to be a paragraph, i.e., only concepts within a paragraph could form a relation.

**Comparison between the two approaches.** By automatic generation of networks there is a risk that the network will not capture the intended information. The choice of window size in this case is critical. With a too large window, however, there is a risk that too many concepts will be linked,
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giving a network with no distinguishable information. A too small window leads to a risk that important links will be lost. A manual building of networks is a very time-consuming process but is expected to capture all the relevant information in the textual data and thus a suitable approach for case studies. However, the more automatic procedure has in the studies of Paper III and IV shown to reveal intelligible results also on small samples. The automatic approach is fast and expected to be reliable enough to be used on large amounts of textual data where students’ mental representations of knowledge and beliefs relatively easily can be determined. However, the networks generated using a more automated process were in these cases further analyzed using a qualitative approach where the networks were used as indicators of where interesting information could be found, taking the analysis one step further. Some context-dependent concepts of particular interest were chosen as prompts in order to locate what type of information their interactions with other concepts carried. Using this approach resulted in determining a number of key aspects associated with computational physics, as described in Paper III.

This is an area that needs further research in order to determine how content analysis and network analysis can be developed towards different implementations in research as well as in educational development.

5.3.4 SOLO analysis

There are different ways of determining the quality of an assignment. The SOLO (Structure of the Observed Learning Outcome) taxonomy (Biggs & Collis, 1982), is a tool for determining quality of learning outcome in terms of complexity based on how students use arguments when explaining and performing a task. The SOLO taxonomy was used for analysis of students’ lab reports in order to determine their quality and get a measure of students’ performance and is described more in detail in Paper I.

5.4 Methodological issues

The purpose with research is to find explanations to phenomena and to find new ways of investigating phenomena. A desire for generalization of results is always present but sometimes it is necessary to investigate a smaller sample or even a case in order to test ideas that could be taken to further research. The studies presented in this thesis are based on small samples and cases and different methods have been used for data collection as well as analysis corresponding to a mixed-method design where both fixed and flexible approaches have been taken (Robson, 2002).
5.4.1 Validity

Validity in research is whether the chosen methods, used for data collection and analysis, are appropriate for measuring the constructs they are supposed to measure. For quantitative data subject for statistical analysis, validation can be done using statistical tools. This was the case in Paper I where the questionnaire data was subject for multivariate analysis methods which provided support for cross-validation and correlation patterns. There are some threats to validity in flexible research designs that generate qualitative data, which I have tried to overcome in this work. The interviews were all audio recorded and transcribed by myself in order to document as much as possible from the interview sessions. When coding the interview transcripts into epistemic elements (Paper II) I mainly used the transcripts but I kept returning to the recordings when I wanted to make sure that I’ve interpreted students intentions and meanings correctly. I did this coding myself and there is always a risk with using only one researcher. However, the choice for content analysis were based on theoretical assumptions of what epistemic elements that were intended to be captured and I chose to reanalyze the data at several occasions with several months apart until the necessary features of the interviews were covered by appropriate epistemic elements. The categorization of words into context-dependent concepts as used in Paper III and IV corresponded to a less sensitive analysis method but used a more exploratory approach than the study in paper II. The categorization procedure was repeated in an iterative process in order to capture all the necessary information that was assumed to describe the particular situation. Using triangulation is a way to increase validity in research. I have in these studies used both quantitative and qualitative approaches, using different methods for data collection as well as for analysis. In order to answer the overall research questions, results from all studies are considered in order to cover the different aspects these approaches have given.

5.4.2 Reliability

Reliability in research is extremely important. In order to be completely reliable an investigation carried out by a research group should generate the same results if repeated by another research group. For flexible research designs this is very difficult to accomplish since the situation for the study changes, especially in education research where unpredictable humans are the subjects for investigations. Different students, different teachers, different curriculums, different environments, even the time of the day or whether it is summer or winter could affect data collection. When collecting and analyzing qualitative data it is suggested to refer to consistency rather than reliability (Lincoln & Guba, 1985). The investigations have been
performed on three consecutive groups of students and generated consistent results where it has been possible. Student beliefs and attitudes, using the same instrument, have been measured in all studies giving student profiles that were consistent through the student groups. A rich description of the studies that have been performed facilitate for reproduction of results and I have tried to include as much information as possible that had to do with the context, the data collection, and the analysis.
6 Results

This chapter presents a summary of the papers and the results according to the research questions that are associated with each paper. In the end of this section the main findings are summarized in relation to the overall research questions presented in chapter 3.

6.1 Paper I: Role of beliefs and emotions in numerical problem solving in university physics education

This study aimed at investigating the correlations between personal characteristics, such as prior knowledge and beliefs, and the emotions that are involved in a high autonomy learning situation, and these variables’ effect on student performance. The research question is posed as:

- What are the relationships between students’ prior knowledge, epistemological and value beliefs, and emotional experiences (control, concentration, and pleasure) and how do they interact with the quality of performance in a learning situation with many degrees of freedom?

The results show that expert-like beliefs about physics and learning physics together with prior knowledge were the most important predictors of the quality of high performance on a task in computational physics offering several degrees of freedom. Feelings corresponding to control and concentration, i.e., emotions that are assumed to indicate a high level of motivation were also important in predicting performance. Unexpectedly, intrinsic motivation, as indicated by enjoyment and interest, together with students’ personal interest and utility value beliefs did not predict performance. This indicates that although a certain degree of enjoyment is probably necessary, motivated behavior is rather regulated by integration and identification of expert-like beliefs about learning. Motivated behavior is thus more strongly associated with concentration and control during learning. The results suggest that the development of students’ epistemological beliefs is important for students’ ability to learn from realistic high-autonomy problem-solving situations in physics education.

6.2 Paper II: Mapping university students’ epistemic framing of computational physics using network analysis

The purpose of the second paper was twofold, having educational as well as methodological issues in focus. The educational purpose was to investigate
changes in students’ epistemic framing before and after doing an assignment in numerical problem solving. Epistemic frames are here referred to as the students’ knowledge and beliefs structures that are activated and revealed when describing (before the task) and recalling (after the task) the assignment in individual interviews. The epistemic networks are built upon epistemic elements, representing different aspects of knowledge and beliefs, as nodes that are connected with links in terms of the interaction between these epistemic elements. The epistemic elements are defined using a thematic coding approach of transcribed student interviews. The purpose was to find, for the context, relevant statements that expressed physics, math, programming, and modeling, but also metacognitive elements expressing epistemology, value, and attributions. The methodological issues also concerned using network analysis as a novel tool for extracting, analyzing, and visualizing the students’ epistemic networks from the transcribed interviews. The research questions of interest in this paper was:

- What are the students focusing on, in terms of knowledge and beliefs, when describing a numerical problem-solving task, before and after doing the task?

- What role does physics knowledge take in describing a numerical problem-solving situation?

The results showed that students had different focus before and after the task, revealed by how the epistemic elements were clustered in each case. Before the task students used descriptive elements and expressed the task in terms of values about learning, in particular Matlab, but also in terms of interest and real world connection. In general they expressed confidence that they would manage the task due to previous knowledge. However, they did express concerns about difficulties with getting started with the assignment but expected that with help from other students and reading the instruction carefully they would indeed manage the task. After the assignment students’ attention turned towards actual experiences of the task where troubleshooting and aspects relating to modeling and programming were in focus.

Students’ use of physics was shown in a 100 % increase in number of unique physics elements in the interviews after the modeling activity. This indicates that, even though no measures on physics knowledge were done in this study, that students were more comfortable with expressing the task in terms of physics concepts after the exercise suggesting an increased understanding of how to use the concepts in this new context of computational physics. This increase was not shown for any other category of epistemic elements.
6.3 Paper III: Mapping university physics teachers' and students' conceptualization of simulation competence in physics education using network analysis

In the third paper an approach to analyze and visualize epistemic networks was used in order to investigate teachers' and students' conceptualization of computational physics. The data was based on interviews with four university teachers with experience from education in computational physics and visualization and six students in computational physics with the purpose of extracting beliefs structures concerning competencies involved in computational physics, such as physics, math, programming, and modeling. The interview transcripts were analyzed using computer-based content analysis generating context-dependent concepts. Semantic networks based on adjacency between concepts were created and visualized as epistemic networks. The research questions were:

- When teachers say that something is important, how is this described in an epistemic network?
- How do students’ epistemic networks change between before and after the task?
- How do students' and teachers' epistemic networks differ? Are students and teachers focusing on the same critical aspects?

These epistemic networks showed that there were similarities as well as differences between how teachers and students framed this particular learning context. The similarities were found in a basic structure where context-dependent concepts describing physics, math, problem solving, programming, and modeling formed a rather stable structure for both teachers and students indicating that they agree about the main characteristics of computational physics. The differences were in the meaning of how these context-dependent concepts interacted and where the focus was. Using the teachers’ networks six key aspects about using computational approaches in physics education could be identified. Teachers saw possibilities to solve deeper and more interesting problems, facilitation of fundamental understanding, and possibilities to control and test the solution but also saw risks that fundamental physics understanding could be hampered if demands of programming and mathematical skills were too large. Students agreed with most of these key aspects, especially after the task. What students did emphasize more was the visual feedback from the simulations and graphs that they used to test and control the simulation.
Students were not all convinced that computational physics would help develop fundamental understanding of physics and math.

A result from this study not reported in the submitted article but still an interesting result, was that the epistemic networks did differ between university teachers with different academic backgrounds. The epistemic networks indicated that the main issue for a teacher with formal background in physics was to use physics principles when investigating a simulation or a solution while for a teacher with formal background in math the focus was on the numerical algorithms. A consequence from this result could be that teachers and teacher assistants with different educational background focus on different aspects of an assignment in computational physics. For example, it could be very difficult to debug and solve a computational physics problem if physics principles such as conservation of energy and momentum are not considered. In order to guide students to solve such a problem the teacher needs to instruct students to also consider physics principles, which might not be the case if the teacher lacks formal education in physics. The other way around is of course also possible. Numerical solutions are usually discrete, meaning that unexpected results due to numerical errors might occur and in that case it is important to understand that the a chosen numerical solution has limitations. From a methodological point of view this result shows additional evidence of that epistemic network analysis is a useful method in order to describe cognitive focus.

6.4 Paper IV: Students' progress in computational physics: mental models and code development

The fourth paper focuses on the students' cognitive process during a one-week computational physics assignment. Students' mental models were monitored using interviews at several occasions during the assignment. As a complement the code the students produce each day was collected in order to get data on students achievements. The interview data was analyzed by content analysis followed by semantic network analysis. The content analysis reduced the transcripts to consist of 101 unique concepts that were content bearing in this particular context. Semantic networks were then created from the reduced transcripts using semantic adjacency as links between concepts. These semantic networks were then assumed to represent students' mental model at the time of the interview. The programming code was also subjected to network analysis in order to find trends in how students built the code for this particular simulation assignment. Students' lab reports were subject for the same content and semantic network analysis in order to see if they reflected students' mental models. The results were presented partly as a compound view of students' shifts in their mental models but also
as a case study, where two students with different beliefs profiles were more carefully investigated.

- How do students' mental models change during the assignment?
- How do students programming code change during the assignment?
- Are there any relations between progress in students' mental models, the characteristics of the code, and the structure of the lab report?

The semantic networks revealed an interesting shift in the students' mental models where the focus moved from being concerned about the difficulties with writing the programming code towards using more and more physics related concepts, especially energy conservation, and expressing less concern about coding difficulties. This was an expected pattern, as similar results were provided in Paper II, but it also means that the method chosen to analyze and visualize mental models did give intelligible results.

The case study showed that students with different beliefs profiles did not use the same concepts when describing difficulties, strategies, and expectations, i.e., they focused on different things. The student with expert-like beliefs focused on how to perform tests on the simulation and to check its performance and had already a coherent view of the whole assignment. The student with novice-like beliefs was focused on the first steps of the assignment and had not yet started to look forward towards a general application.

The student with expert-like beliefs also used a more general coding approach, developing a code that would apply to all steps in the assignment. The code thus was only slightly changed between the submissions and kept its general structure all the way into the lab report. A student with novice-like beliefs started with an approach that would solve only the first step in the assignment, coding a special case rather than a general case. As the assignment turned more complex this student had to rewrite large parts of the code in order to match the general case and solve all steps in the assignment.
7 Discussion of main findings

I here summarize and discuss the main findings as answers to the research questions stated in chapter 4 given by the empirical data in relation to previous research.

7.1 Critical aspects of computational physics

- What are the critical aspects of computational problem solving in physics education with respect to the relationship between student characteristics, progress, and performance?

Students' beliefs about physics and learning physics have in these studies shown to be important predictors of performance in computational physics. The task described and investigated in this thesis corresponded to a learning situation which provided many degrees of freedom and participants who believed that invested effort and taking responsibility of one’s own learning, performed better in this task. The learning situation’s characteristics were also mirrored in the students' perceived control and concentration emotions, which are important indicators of motivation, showing that this assignment provided scope for self-determined behavior.

Even though previous research stresses the importance of including students' motivation in successful learning (Eccles & Wigfield, 2002; Ryan & Deci, 2000) it is mainly the cognitive aspect of motivation, represented by the emotions concentration and control, that contribute to performance in the particular context described in this thesis. Emotions expressing enjoyment and value are often used as indicators of intrinsic motivation (Pekrun, 1992; Turner, Meyer, & Schweinle, 2003), but in Paper I they showed little correlation with performance in this particular context. Thus, the results imply that it is not enough to just be interested and value the task as useful in order to perform well, the task must also be optimized for cognitive engagement in order to motivate students.

The assignment used in these studies represented a complex learning situation where knowledge and skills from several domains were needed in order to perform well. The learning situation also provided several degrees of freedom where students could choose when, where, and how to solve the problem, characteristics that are related to the level of autonomy of a task. Previous research has, however, shown that not all students perform well in a high autonomy learning situation. It is mainly those students who already possess expert-like beliefs that are more likely to be favored by a learning situation with many degrees of freedom (Redish et al., 1998; Windschitl & Andre, 1998). Autonomy is one of the needs, i.e., reasons to engage in an
activity, in self-determination theory, together with competence and relatedness (Deci & Ryan, 1980), and is suggested to be indicated by perceived emotions of control (Ryan & Deci, 2000). The results reported in Paper I show that competence and control are indeed predictors of performance and correlated with epistemological beliefs and prior knowledge. This indicates that students who experienced self-determination also reported expert-like epistemological beliefs and scored high on performance, which supports previous research on these correlations.

Thus, epistemological beliefs and prior knowledge are not only reliable predictors of performance but also important to consider when designing learning to support self-determined behavior. Students with novice-like beliefs tend to view knowledge as consisting of isolated facts and something possessed and transferred by authority. They risk experiencing difficulties with approaching an assignment that requires a coherent use of different knowledge and skills and several alternatives to reach a solution. Students need to feel competent but if their view of competence differs from what is expected from the assignment I suggest they need triggers to motivate them towards a self-determined behavior, such as positive and constructive feedback on competence.

7.2 Teachers' and students epistemic framing

- How do teachers and students frame a learning situation in computational physics? Do teachers and students agree about learning objectives, approaches, and difficulties?

Teacher’s beliefs have in previous research been suggested to have impact on how teaching is performed and how teaching material is developed (Henderson, Yerushalmi, Kuo, Heller, & Heller, 2007; Louca, Elby, Hammer, & Kagey, 2004; Yerushalmi, Henderson, Heller, Heller, & Kuo, 2007). In Paper III, teachers’ beliefs about computational physics were investigated using a network analysis approach in order to map what teachers believed was important aspects of computational physics. Since there is an assumption that teachers' intentions correspond to students' expectation a comparison between teachers' and students' epistemic networks was included in the study.

One of the most important aspects is that teachers view computational problem solving in physics as something that students can actively engage in to a higher degree than analytical problems, which have limitations in what type of questions and phenomena they can treat. Teachers claim that possibilities to test, interact with, and control the solution open up for increased understanding of physics, as well as math and the numerical methods. This mirrors teachers’ epistemological beliefs, i.e., how they
believe their students learn and how they want them to learn. The teachers interviewed in Paper III all expressed beliefs about learning corresponding to active engagement and making use of previous knowledge to develop new knowledge. However, no observations of teaching have been made in these studies and previous research has also shown that even though teachers believe that students should be actively engaged in their own learning it is not always reflected in how the teachers teach (Van Driel, Verloop, Inge Van Werven, & Dekkers, 1997).

Teachers see the possibilities for students to investigate more realistic physics problems with the use of numerical tools and expect that students will develop a deeper understanding of physics as well as math and numerical methods. Students do agree with these beliefs to some extent but do not express development of fundamental understanding to the same degree. If they do, it is related to the visual feedback. The feedback aspects of the visualizations of the problems are present in all interview studies and seem to encourage a motivated behavior where students stick to the task, possibly indicating a deepened cognitive activity, which could eventually lead to development of expert-like knowledge, and thus beliefs.

Teachers believe that the students would appreciate complex problems because the teachers see both the possibilities of solving more interesting problems but also to be able to look beyond the more surface-like and idealized features that analytical problems are limited to offer and develop a deeper understanding. However, the students are not expected to have the problem solving experiences associated with numerical tools or subject knowledge that experts have. They have not acquired that knowledge yet. This might cause a gap between what teachers teach and what students learn (McDermott, 1991). Students express that they probably won’t acquire any deeper understanding of physics because they are occupied with the numerical implementation. Maybe they are not able to see the possibilities to reach deepened physics understanding because they actually do need more practice and more experience in order to construct the mental representations that are useful as working models for developing conceptual knowledge in physics. However, students are confronted with physics principles as well as mathematical methods and programming issues during the assignment, but the impact on how they conceptualize the learning situation is dominated by an increased used of physics. This indicates increased physics awareness.

In the present case of computational physics the teachers shared many of the beliefs about the learning situation, as reported in Paper IV, but there are differences that mainly have to do with the subject field the teacher originally belongs to. A teacher with his/her roots in computer science may not at first hand consider that a student’s problem with a solution could be troubleshooted by applying fundamental physics laws. On the other hand a
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teacher schooled in physics or math may lack the insight in how data structures and algorithms contribute in order to build effective computer programs. This thesis does not investigate aspects of learning computer science but previous research in this field stresses the importance of gaining knowledge about, e.g., concurrency, data structures, and algorithms, in order to become proficient programmers (Moström, 2011).

7.3 Positive and negative learning effects

What are the consequences in terms of positive or negative learning experiences from using computational problem solving in physics education?

The results from Papers I and IV show that students who already possess expert-like beliefs seem more likely to be favored by a learning situation that provides conditions for autonomous learning behavior. This is in line with previous research (Redish et al., 1998; Windschitl & Andre, 1998).

The results from Papers II, III, and IV imply that the visualization aspects of the particular assignment used in these studies are very important for the students. They use the visual simulation and graphs to evaluate their numerical solution and they also express the visual feedback as a resource for better understanding. The results also show that students to a higher degree use physics concepts after the task, which indicates that students feel more confident with physics terms. Previous research has shown that whether a problem used visual feedback or numerical feedback had influence on how students solved problems (Monaghan & Clement, 2000). With a numerical solution students were more likely to use algorithmic arguments while a visualization made students use mental imagery to solve the problem. Monaghan and Clement suggested that a combination of visual and numerical representations could lead to better, more coherent understanding of phenomena involved in a problem. The assignment used as context in my studies did encourage both modalities and is thus expected to lead to a more coherent understanding of the task than if only one of the numeric or visual feedbacks were provided. The results from Papers II, III, and IV did show an increased awareness in physics in terms of using more concepts expressing physics. However, the cognitive depth in how these concepts are used are not investigated in detail but I suggest that students’ learning experiences points towards an increased understanding of physics in this particular context indicated by the increased interactivity between physics concepts and other context-dependent concepts.
7.4 Network analysis as a tool

What are the strengths and weaknesses of using network analysis as a tool for analyzing and visualizing knowledge and beliefs structure?

Network analysis seems to be a useful tool for extracting different types of representations from textual data, generated from interviews, lab reports, or programming code. The idea of expressing cognitive structures as networks is not new and there are several studies besides mine where networks are used as representations of epistemic framing (Shaffer et al., 2009), mental models (Carley & Palmquist, 1992; Jonassen & Henning, 1996; Shavelson, 1972), and knowledge structures (Koponen & Pehkonen, 2010). My contribution to this field is to develop relatively simple content analysis methods to generate semantic networks and visualize them using a map generator optimized for dynamic clustering of nodes (Rosvall et al., 2009). In the studies reported in this thesis network analysis has been used with different approaches. In the study reported in Paper II, the content analysis, based on manual coding of interview transcripts, was visualized as epistemic networks describing students' epistemic framing of a computational physics assignment. The epistemic networks revealed structures in students' framing showing how students' focus changed between before and after the assignment.

In Papers III and IV network analysis was used as computer-assisted content analysis. The textual data was subjected to text-mining processes where words were categorized according to their content-bearing characteristics in the particular context. The textual data could then be reduced to contain only a limited number of context-dependent concepts, 26 concepts in Paper III and 101 concepts in Paper IV, which were assumed to still maintain the content and meaning of the texts. This content and meaning were visualized by generating semantic networks from the reduced texts, allowing concepts that were close and belonging to the same sentence to be connected. The resulting epistemic networks could then be regarded as representations of the conceptualization of the investigated texts. I further assumed that these networks based on interviews could be interpreted as mental models, revealing what was on an individuals mind at the time of the interview.

Even though the applications of epistemic networks are somewhat different between the studies in Papers II, III, and IV the method follows the same basic procedure. Striking is that the semi-automated content analysis approach used in Papers III and IV does give intelligible information from the data that is very similar to the qualitative analysis performed in Paper II, categorizing and connecting statements manually. Thus, an automated
process seems useful in order to indicate patterns of content and meaning in many contexts that can be represented textually.

One critical issue lies in how the concepts that would represent the context are chosen. I have used two approaches: One that is similar to traditional qualitative coding of textual data where epistemic elements (statements) expressing knowledge and beliefs are identified as nodes in the epistemic network, Paper II. The choice of epistemic elements was based upon a confirmatory approach where certain types of knowledge, beliefs, and resources (principle categories) were searched for but the actual epistemic elements were defined using an exploratory approach. The other way of choosing concepts among a complete word list followed an even more exploratory approach. The only limitation was that they would represent a meaning in the context. Using a smaller number of concepts generate a coarse-grained network as investigated in Paper III, while more concepts, as in Paper IV, would give a finer grained network with more information.

Another critical issue concerns how the linking is determined and how I know that the resulting network represent the structure of meaning of the original data. Since I have used very simple linking options, based almost only on adjacency, there are limitations to what questions these networks can give information about. In Paper II, the relations between the epistemic elements were qualitatively treated, where links were defined considering semantic adjacency. By using the original transcripts as references it was possible to make sure that no important links were missing. However, the linking was limited to only show that there was a relation, not what type of relation. In order to add meaning to the networks the links could contain more information, e.g., direction, strength, meaning (Carley & Palmquist, 1992), and that information could be provided in a visualization. I suggest this as an area of research that needs to be developed further in order to capture more fine-grained information and facilitate qualitative interpretation of the networks.
8 Conclusions

The work I present in this thesis contributes to physics education research in several aspects. Using interactive tools for modeling physics and technology, building simulations, and interactive solutions is expected to grow in tertiary physics education as well as in secondary and even primary education due to increased use of interactive tools and environment in learning. Knowledge about students' affective and cognitive reactions in these learning situations is therefore important to consider. I have provided the following contributions to this field of physics education research:

- I have investigated a new and emerging area in tertiary physics education, namely computational physics.

- I have shown that students' epistemological beliefs are important predictors for students' performance.

- I have shown that it is not enough to be interested and value the task as useful in order to perform well, the task must also be optimized for cognitive engagement in order to motivate students.

- I have shown that students increase their physics awareness during an assignment in computational physics.

- I have introduced a novel method of modeling knowledge and beliefs structures using network analysis in educational research.

This thesis highlights some of the critical aspects that are related to teaching in computational physics. Introducing learning activities offering possibilities for high autonomy and complexity but it is important to consider how students' beliefs, epistemological as well as value, might influence student behavior. Computational physics is not easy to students. There are many aspects that students need to relate to and as a teacher it is important to guide the student to a coherent view of the computational problem without losing physics, mathematical, or programming aspects. To keep focus on the importance of how physics principles are used in troubleshooting problem solutions is one suggestion to help students to a coherent view. I suggest that teachers emphasize the limitations and possibilities that numerical methods may provide in solving physics problems.

Improved understanding of how complex learning situations, such as in computational physics, affect student with different profiles in cognitive as
well as in motivational aspects could provide a good platform for development of assignments to support efficient learning. Further development of methods for modeling of knowledge and beliefs structures is therefore suggested as an emerging area of research.
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