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Risto Leinonen

# *Improving the learning of thermal physics at university*

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EASTERN FINLAND

**RISTO LEINONEN**

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Academic Dissertation
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**ABSTRACT**

This dissertation is intended to address university students' conceptions concerning thermal physics in introductory-level physics courses. The aim of the study has been to improve learning about the first law of thermodynamics, thermal processes, and the interdependences for certain quantities by means of an innovatory lecture-based teaching intervention.

The principal aim of the research has been divided into three sub-aims related to students' conceptions in different phases of the studies: (a) prior to instruction, (b) following conventional lecture-based teaching, and (c) during and after the teaching intervention. Constructing the intervention referred to in the third sub-aim was also a significant component of the study since it focuses on improving learning. Hence, the principal research aim, that of improving learning, is built in to the entity of the sub-aims, even if it is not explicitly indicated in the individual sub-aims themselves. To obtain a wide-ranging view of students' conceptions, data was collected with the aid of paper-and-pencil tests, semi-structured interviews, and audio recordings.

Prior to the start of instruction, students harbored various misconceptions. They did not differentiate between concepts such as temperature, heat, and thermal energy. With regard to work, students did not seem to understand how it relates to thermodynamics. This insight was reinforced when students' explanations concerning adiabatic compression of an ideal gas were evaluated: students evidently did not understand the relevance of the concept of work and the first law of thermodynamics, relying rather on other explanations such as the ideal gas law and microscopic models. Moreover, it was revealed that students were oblivious of the inconsistencies and deficiencies in their reasoning.

Conventional lecture-based teaching left students with various misconceptions. A majority of them had various problems concerning the process quantities of heat and work. Other prevalent misconceptions were observed: the impact of work on

internal energy was ignored, isothermal and adiabatic processes were not distinguished, and the interdependencies for quantities were misunderstood. One prevalent problem, although not a misconception per se, was the absence of their use of *pV* diagrams. Only a few individuals used these spontaneously when determining the work involved in thermal processes, despite the emphasis that had placed on the diagrams in the teaching that they had received previously.

Inspired by these findings, an innovative teaching intervention was constructed to supplement the conventional lecture-based teaching. The intervention is based on scaffolding, which refers to the processes whereby the learner is helped in successfully completing otherwise unachievable tasks.

In the present study, therefore, scaffolding was implemented in the form of content hints and peer discussions. To this end, the intervention consisted of four phases: an individual working phase, two hinting phases related to physics content, and a peer interaction phase. The intervention took place in the lecture setting, but only after the necessary content had been introduced in earlier teaching.

With respect to the third research aim, the intervention helped students to achieve a better learning outcome, the real change being statistically significant in most of the tasks. Compared to previous studies, our intervention produced a 15-20 percentage point enhancement in the learning outcome. We also observed a reduction in the percentages of misconceptions, with individual exceptions. Similar follow-up results in the post-testing showed that the impact of the intervention was not short-lived.

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# *Preface*

Firstly, I wish to thank the institutions funding this research project: the Finnish Cultural Foundation, the Finnish Graduate School of Mathematics, Physics, and Chemistry Education, the Department of Physics and Mathematics, and the Faculty of Science. Besides enabling full-time working, the aforementioned quarters have offered me chances for valuable and enjoyable visits to various interesting locations.

The deepest imaginable gratitude goes to my supervisors Pekka E. Hirvonen and Mervi A. Asikainen. Your support and guidance has been crucial not only for this research but also for me. I have absolutely no idea how supervising could get any better. Thank you.

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Moreover, the support of the personnel in our department is acknowledged; coffee breaks might not help with problems but they surely make them easier to tolerate. Especially I want to thank the following colleagues and friends: Mikko, Ville, Ismo, Jussi, Kalle, Tommi, Petri, Janne, Jarno, and Ville. I owe you big time.

The warmest thanks go to my parents Reino and Inkeri. Without your never-ending support this book would not exist. Also, my siblings Kaisu, Tommi, and Teemu with his family deserve special thanks. You’re the best.

Finally, thank you Tina. We both know why.

Joensuu, August 29, 2013 *Risto Leinonen*

## LIST OF PUBLICATIONS

This thesis is based on data presented in the following articles, referred to by the Roman numerals I-V.

**I** Leinonen, R., Räsänen, E., Asikainen M. A., and Hirvonen, P. E. (2009). Students' pre-knowledge as a guideline in the teaching of introductory thermal physics at university. *European Journal of Physics, 30,* 593-604. (Reprinted with kind permission by IOP)

**II** Leinonen, R., Asikainen M. A., and Hirvonen, P. E. (2012). University students explaining adiabatic compression of an ideal gas – A new phenomenon in introductory thermal physics. *Research in Science Education, 42,* 1165-1182. (Reprinted with kind permission by Springer)

**III** Leinonen, R., Asikainen M. A., and Hirvonen, P. E. (Submitted). Applying the contents of thermodynamics in a multi-phased process in university – What is the problem? Submitted to The proceedings of the GIREP-ICPE-MPTL 2010 conference.

**IV** Leinonen, R., Asikainen M. A., and Hirvonen, P. E. (2012). Hints and peer-peer-interaction in the learning of university thermal physics. In A. Lindell, A.-L. Kähkönen, and J. Viiri (Eds.), *Physics Alive: Proceedings of the GIREP-EPEC 2011 Conference, (pp. 92-97). Jyväskylä: University of Jyväskylä.* (Reprinted with kind permission by the editors)

**V** Leinonen, R., Asikainen M. A., and Hirvonen, P. E. (2013). Overcoming students' misconceptions concerning thermal physics with the aid of hints and peer interaction during a lecture course. *Physical Review Special Topics – Physics Education Research, 9,* 020112. (Reprinted with kind permission by APS)

## AUTHOR'S CONTRIBUTION

The author has designed data collection methods and collected data for articles III, IV, and V and partly for article II. Concerning the data analysis, the author had the main responsibility in articles II-V and he participated in the analysis in article I. The author designed the teaching intervention with the assistance of his supervisors. With respect to formulating the theoretical background of the articles, the role of the author has increased progressively throughout the progress of the research. The author has undertaken the major part of the writing of all of articles I-V.

# Contents

# 1 Introduction

Learning and understanding physics can be quite a challenge. Even if the formulas may appear simple, applying the corresponding principles in physical situations has been shown to be problematic for learners, especially when no calculations are required. This study concentrates on evaluating and improving university students' ideas concerning the essential topics of thermal physics at an introductory level.

## 1.1 MOTIVATION

My own first steps in physics were not too difficult. I achieved decent grades in the lecture courses by following the lectures, doing the homework, and preparing for exams. During the third year of my studies, I participated in a course on Conceptual Physics for Teachers. This course caused me to realize that, despite my reasonable success thus far with the study of physics, my understanding of physical phenomena in terms of concepts and their dependencies was inadequate. The ostensibly simple tasks revealed flaws in my content knowledge, in other words, I was the victim of misconceptions. This showed me that physics is not simply a case of doing calculations but that it consisted of phenomena that can be approached differently, conceptually. In sum, following this revelation, physics appeared to be even more interesting to me than previously.

Later, I wrote my Master's thesis on university students' conceptual understanding of electricity and magnetism. The research involved in that project proved to me that even relatively simple physics phenomena can reveal serious problems in students' content knowledge. Moreover, it caused me to ponder on the underlying reasons for such misconceptions, since it was evident that university lecturers themselves have expertise in the field, and hence it was unlikely that they were the origin of these inaccurate ideas.

While I was in the process of completing my Master's degree studies, my supervisor Pekka Hirvonen asked if I would like to continue doing research, this time concentrating on the learning and teaching of thermal physics, which appeared to be an area that had thus far not been subjected to thorough study. Hence, the motivation of the present research project emerged from a natural interest in conceptual physics and from positive experiences that I received while engaged in working on physics education research.

### 1.2 RESEARCH PROCESS

The original idea of this research was to evaluate university students' understanding of the first and second laws of thermodynamics at university level, and to describe the learning processes undergone by students during a course in thermal physics. The first phase involved collecting data concerning students' conceptions based on their secondary-level studies. This data revealed serious flaws in their understanding of the essential concepts of thermal physics and of the application of the first law of thermodynamics in the case of adiabatic compression of an ideal gas.

The next phase was concerned with evaluating students' conceptions of thermal processes following exposure to conventional lecture-based teaching. This revealed that lecture-based teaching supplemented with homework sessions left a majority of students with various problems concerning essential thermal physics content, especially that related to processes and to the first law of thermodynamics.

These findings inspired us to specify the focus of our research. Instead of describing students' learning processes involved in understanding the two laws of thermodynamics, we decided to concentrate on improving students' learning outcome in relation to the following topics: the first law of thermodynamics, thermal processes, an equipartition theorem, and the concepts related to these. One of the reasons for concentrating on these topics was the fact that mastering them provides a great explanatory power for dealing with the numerous phenomena of thermal physics. In addition, mastering these topics was of primary importance for understanding other essential topics, such as the second law of thermodynamics and the physics of heat engines.

### 1.3 RESEARCH AIMS

The principal aim of this research project has been to improve introductory-level students' conceptual understanding of the essential thermal physics content in a way that does not require special training or resources but which can be applied in an ordinary lecture setting. To achieve this aim, the research project can be thought of as divided into three parts, each of which has its own sub-aim. These sub-aims are as follows:

i. *To figure out and describe introductory students' conceptions and reasoning concerning thermal physics prior to instruction*
ii. *To figure out introductory students' conceptions concerning thermal physics after conventional lecture-based teaching*
iii. *To evaluate introductory students' conceptions during and after an intervention addressing students' well-known misconceptions*

The aim of improving students' conceptual understanding is not seen explicitly in the sub-aims, but it is nevertheless included implicitly in their entity. The first two sub-aims were formulated to evaluate the need for teaching to be improved. The results related to these sub-aims, combined with previous research findings, guided us in the construction of a teaching intervention aimed at improving students' conceptual understanding. Sub-aim *iii* addressed students' conceptions during and after the intervention so that the impact of the intervention could be evaluated. Although the intervention is a significant part of our research project, constructing it is not introduced as an individual sub-aim because the value of the intervention emerges from the results obtained with it, as addressed in sub-aim *iii*.

The sub-aims are addressed in research articles I to V. The first sub-aim is pursued in articles I and II, which present detailed descriptions of students' conceptions, explanations, and reasoning prior to receiving instruction. The second sub-aim is focused on in article III, which offers a concise overview of students' conceptions after conventional teaching. Sub-aim *iii* concerning the impact of the intervention is approached in articles IV and V. Article V also touches in part on sub-aims *i* and *ii*.

### 1.4 STRUCTURE OF THE DISSERTATION

Section 2 is devoted to introducing the thermal physics content and also previous research concerning misconceptions and teaching interventions related to essential thermal physics topics. Methodology, a context, and samples for the study are introduced in section 3. Designing and implementing the innovatory teaching intervention is introduced in section 4. Section 5 provides an overview of the results obtained. The final section 6 addresses the research aims, legitimation, and conclusions and outlook of the study.

# 2 Basics of thermal physics and previous research

This section introduces the essential thermal physics content followed by a review of the literature introducing students' misconceptions and other related problems at university and upper secondary levels. The final section introduces some of the teaching interventions implemented in the field of thermal physics.

## 2.1 BASICS OF THERMAL PHYSICS

*Thermal physics* is an area of physics that examines the behavior of systems consisting of a great number of particles. When a macroscopic system visible to the human eye is under observation, the number of particles may be $10^{23}$ in magnitude. This means that following and observing individual particles is meaningless, if not impossible. Assumptions concerning the motions and interactions of particles and the probabilities of different outcomes can, however, be used to predict the behavior of a system on a macroscopic level, a fact that refers in turn to the key idea of *statistical mechanics*.

Statistical mechanics has a great explanatory power. With its assistance, for example, the direction of heat transfer and the efficiency of heat engines can be understood. Some of the results of statistical mechanics can then be generalized to make up a theory of *thermodynamics*, in other words, the study of the transformation of energy. (Atkins & De Paula, 2006; Schroeder, 2000)

The general context for the physics involved in the present study is provided by the ideal gas processes, which students are required to understand and explain from the perspectives of energy transfer and microscopic models. The physics required to understand and explain these processes includes the equipartition theorem, the first law of thermodynamics, and the ideal gas law (Knight, 2008; Schroeder, 2000; Young & Freedman, 2004). The following subsections introduce this thermal physics content in a concise but adequate way in order to provide a clear understanding of the ways in which our results are concerned with students' conceptions.

### 2.1.1 Equipartition theorem and temperature

We can start this study by examining a single gas particle, namely a molecule in a three-dimensional space. Depending on its molecular structure, a molecule can store energy in the form of its translational kinetic energy, its rotational energy, its vibrational motion, and its elastic potential energy. The number of these forms of energy defines the *degrees of freedom* of a molecule. This number varies depending on the molecular structure. For example, a diatomic molecule in a gaseous state has three degrees of freedom ($x$, $y$, and $z$ directions) for translation motion, two for rotational kinetic energy, and potential and kinetic parts for vibration (Figure 2.1). Thus, a diatomic molecule may have a maximum of seven degrees of freedom. The real number of active degrees of freedom depends on temperature, since at low temperatures some degrees of freedom do not contribute to the energy of a molecule. (Schroeder, 2000) In the present study, we will concentrate on systems where the number of degrees of freedom is assumed to remain constant despite potential temperature changes.

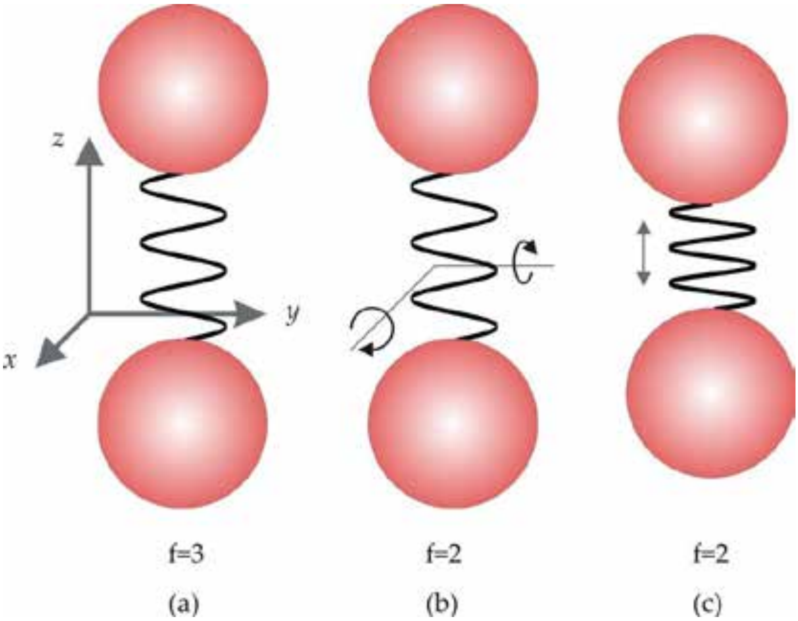

***Figure 2.1***. *Degrees of freedom for a diatomic molecule: a) three for translational kinetic energy, b) two for rotational kinetic energy, and c) kinetic and potential energy for vibrational motion.*

*The equipartition theorem* is an essential statement that connects the energy of a particle to temperature $T$ and to the degrees of freedom. The average energy of any degree of freedom is ½$kT$, where $k$ stands for the Boltzmann constant, $1.38 \times 10^{-23}$J/K. This means that the average *thermal energy* $U_{th}$ of a system consisting of $N$ molecules, each with $f$ degrees of freedom, can be represented as (Blundell & Blundell, 2006; Knight, 2008; Schroeder, 2000)

$$U_{th} = ½NfkT. \quad (2.1)$$

When we examine monatomic molecules, another interesting finding emerges. An atom has only three degrees of freedom, that is, those related to translational kinetic energy. Based on the equipartition theorem, the average translational kinetic energy $K_{trans}$ of a single atom can be written as $K_{trans} = \frac{3}{2}kT$. On the other hand, the average kinetic energy of an atom with mass $m$ and velocity $\bar{v}$ can be expressed as $\frac{1}{2}m(v^2)_{avg} = \frac{1}{2}mv_{rms}^2$. Root-mean-square speed $v_{rms}$ refers to the square root of the average of the squares of the speeds. When these equations concerned with average kinetic energy are combined, we find a connection with the root-mean-square speed of a particle and temperature (Knight, 2008; Schroeder, 2000)

$$v_{rms} = \sqrt{\frac{3kT}{m}}. \tag{2.2}$$

The previous equations provide important connections concerned with temperature, the thermal energy of the system, and the translational kinetic energy of particles.

### 2.1.2 The first law of thermodynamics

The law of conservation of energy is unquestionably one of the best-known and most powerful principles of physics (Knight, 2008; Young & Freedman, 2004). *The first law of thermodynamics* is a form of this statement that concentrates on change in the energy of the system via two types of mechanisms: *heat* and *work*. Normally, the energy under inspection in thermodynamics is *internal energy* $U$, which consists of all forms of microscopic energy: in addition to thermal energy, internal energy also includes chemical energy and nuclear energy, for example. In the present study we concentrate on simple systems for which a change in internal energy is always seen as a change in thermal energy. (Knight, 2008). The first law of thermodynamics can be written in a mathematical form as

$$\Delta U = Q + W, \tag{2.3}$$

where $\Delta U$ is change in the internal energy of the system, $Q$ is heat, and $W$ is work. One should remember that heat and work always refer to energy in transfer, and hence they are labeled *process quantities*. They cannot be used to describe any actual state but refer only to changes in the state.

Heat $Q$ is defined as *a spontaneous energy flow between two objects causes by a temperature difference* (Chabay & Sherwood, 2011; Knight, 2008; Schroeder, 2000; Young & Freedman, 2004). According to the second law of thermodynamics, energy flows spontaneously from higher temperature to lower temperature, and this energy in transfer is called heat[1] (Knight, 2008). This property can also be utilized in defining *temperature*: it is *a measure of an object's tendency to give up or receive energy spontaneously* (Schroeder, 2000). On a microscopic level, heat is a consequence of two particles with different kinetic energies colliding; it is highly probable that the particle with higher kinetic energy loses energy to the particle with lower kinetic energy (Chabay & Sherwood, 2011).

Work $W$ includes all the other forms of energy transfer (Schroeder, 2000). For example, work can be mechanical, electrical, or done by electro-magnetic waves. The applicable definition for mechanics and thermodynamics states that work is *the transfer of energy by motion against an opposing force* (Atkins & De Paula, 2006). In this study, our focus is on mechanical compression or expansion work done on the gas. By utilizing the definition of work as it appears in mechanics and the connection between pressure $p$ and force $F$, a compression work done on the gas can be expressed as follows:

$$W = -\int_{V_i}^{V_2} p(V)dV, \qquad (2.4)$$

where $V$ is volume. This is helpful in the sense that, with the aid of pressure vs. volume diagrams, aka $pV$ diagrams, work can be determined as the area under the curve with a reversed sign. (Knight, 2008; Schroeder, 2000) This property will become practical in the next section, which introduces the well-known ideal gas law and thermal processes.

### 2.1.3 Ideal gas law and thermal processes

Experiments conducted with gases in the 17th and 18th centuries revealed an interesting connection for four state variables:

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[1] Probabilities for the direction of heat transfer can be calculated for different models of matter, and it is seen that for macroscopic systems the direction from higher temperature to lower temperature is inevitable; the probability of heat transfer from lower temperature to higher temperature is negligible.

pressure $p$, volume $V$, absolute temperature $T$, and the number of moles $n$ (Blundell & Blundell, 2006; Knight, 2008). The results of these experiments are summed up as *the ideal gas law*

$$pV = nRT, \tag{2.5}$$

where $R$ is the universal gas constant, $8.31 \frac{\mathrm{J}}{\mathrm{K\,mol}}$. This is an approximate law, in fact a model that functions well for low-density gases. It has its limitations in extreme conditions, such as in low temperatures, but in the present study it can be applied to all of the gas systems under inspection. (Knight, 2008; Schroeder, 2000) It is often useful to write the equation in a form where two states, 1 and 2, with an equal number of moles are examined:

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \tag{2.6}$$

When the behavior of a gas system from the perspective of the first law of thermodynamics is subjected to examination, the ideal gas law proves to be useful. In the following, we will introduce four particular thermal processes for an ideal gas. We will concentrate in particular on processes where the gas system is *closed*, which means the number of moles remains constant throughout all of the processes.

In *isochoric heating* the gas system is heated and its volume is fixed to remain unchanged. By applying equation 2.6, it can be seen that an increase in temperature causes the pressure to increase. Because volume remains constant, work can be calculated with the equation 2.4 and equals zero, which means that only heat affects internal energy. In the heating process both $\Delta U$ and $Q$ are positive, while the opposite cooling process indicates them to be negative (Knight, 2008). A $pV$ diagram illustrating the process is seen in Figure 2.2a.

In *isobaric heating* the gas system is heated so that the pressure is fixed to remain constant, typically in a frictionless cylinder-piston system. Heating the gas means that heat $Q$ is positive. Newton's third law and definition of pressure applied to the piston states that the volume of the gas increases during

isochoric heating which means that negative work $W$ is done on the gas. When volume increases in the isobaric process it also means an increase in temperature and in the internal energy of the gas. Hence, in the case of an isobaric heating process a change in the internal energy is positive, although part of the heat is used for expansion work. With the help of equation 2.4, work can be calculated: $W = -p\Delta V$. (Knight, 2008) The process is illustrated in Figure 2.2b.
During *isothermal compression* the temperature of the gas is held constant by compressing the gas slowly so that it is constantly in thermal equilibrium with its surroundings. Work can be calculated with the help of equations 2.4 and 2.5, giving the result $W = -nRT \ln \frac{V_2}{V_1}$, which is positive for a compression process. Based on equation 2.1, a constant temperature indicates that the internal energy remains unchanged. Based on this and on the first law of thermodynamics, it can be concluded that heat $Q$ is equal to work but the opposite in sign. Figure 2.2c represents the process in a $pV$ diagram.
The fourth process is termed *adiabatic compression*, in which heat cannot escape from the gas due to a rapid process or *insulation*. When heat $Q$ equals zero, the internal energy is changed only as a result of work done on the gas, which is positive in a compression process. When temperature change $\Delta T$ and the number of degrees of freedom $f$ for the gas are known, the work done during an adiabatic compression process can be calculated. The mathematical dependency for pressure and volume is expressed as $pV^{\frac{f+2}{f}}$ = constant. (Schroeder, 2000) A $pV$ diagram of the process can be seen in Figure 2.2d.

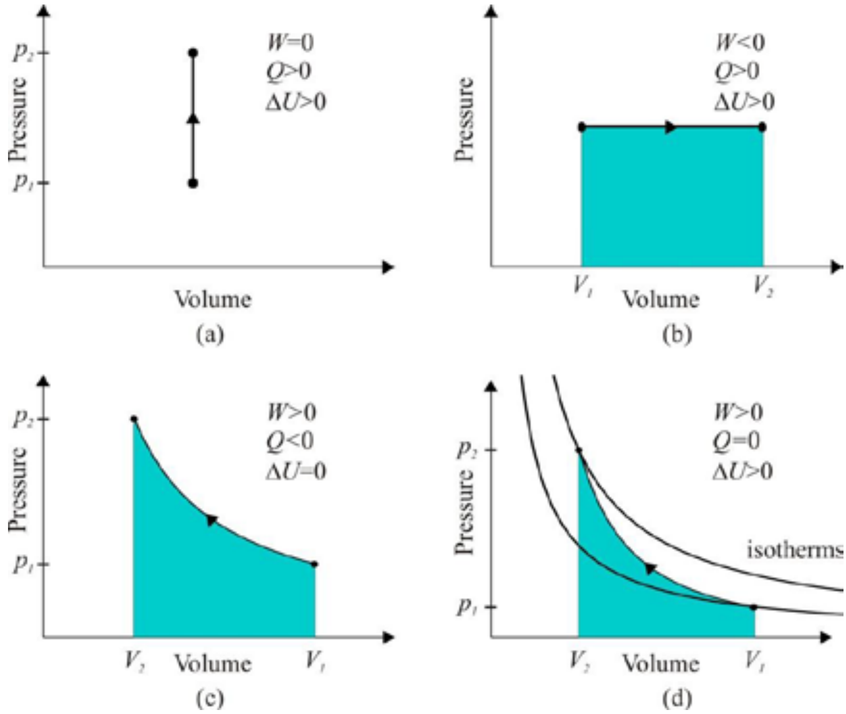


***Figure 2.2***. *pV diagrams and signs for work, heat, and change in internal energy for a) isochoric heating, b) isobaric heating, c) isothermal compression, and d) adiabatic compression (f=3) processes. The shaded areas illustrate work done during the process.*

### 2.1.4 Summary

Individually, the principles mentioned above have only a relatively modest explanatory power in relation to gas processes. If any of the pieces, be it the equipartition theorem, the first law of thermodynamics, or the ideal gas law, is missing, any explanation of gas processes inevitably remains insufficient. But the entity of these principles has a great explanatory power in relation to gas processes, and they are a prerequisite for understanding the physics of heat engines and cooling systems, for example.

## 2.2 STUDENTS' MISCONCEPTIONS

Research conducted in the field of the learning and teaching of thermal physics has been rather extensive in the course of recent decades. The first articles were published in the 1970s (Warren, 1972; Zemansky, 1970), and since that, dozens of research projects related to the learning and teaching of thermal physics have been conducted and reports published. In consequence, this section provides an overview of the most essential findings regarding the understanding at university and upper secondary levels of the concepts, the first law of thermodynamics, the ideal gas law, and thermal processes.

In the discussion of students' inaccurate ideas about the concepts, laws, or phenomena, the term *misconception* is used throughout the present dissertation.

This particular term has been subjected to criticism because of its negative nuances, but we consider it to be the most suitable one in this type of university-level research for describing students' inaccurate conceptions. In our use, the term is based on the disparity between a student's idea and the content taught (Clement, Brown, & Zietsman, 1989; Vosniadou, 2002). Other possible terms such as preconception or alternative conception would pose problems in the reporting phase: preconception is an illogical term when evaluating conceptions held at various stages of studies, whilst alternative conception as a term makes it more difficult to distinguish the desired conception from the inaccurate ones. In the following, the use of the term misconception is opened up by introducing four criteria presented by Hammer (1996), and by discussing how these compare to our use of the term.

The first criterion states misconceptions to be strongly held and stable (Hammer, 1996). We do not take a strong stand on this issue, but misconceptions can also be adaptable and context-dependent, and students may possess more than one misconception concurrently. Stability, in our use, means that in a limited context students tend to rely on some specific conceptions that are relatively resistant to change.

The second criterion argues that misconceptions differ from expert conceptions (Hammer, 1996). In our use, this means that all ideas differing from the desired conception are regarded and labeled as misconceptions. This includes misunderstanding concepts and applying physics principles inadequately, for example.

The third criterion is closely related to the second one: misconceptions affect students' understanding of natural phenomena and their explanations (Hammer, 1996). We see this as, in a sense, a rather self-evident criterion because if misconceptions had explanatory power with great accuracy and area of applicability, they would not be misconceptions. In our use this criterion is regarded as saying that the explanatory power of misconceptions is more limited than that of scientific conceptions.

The fourth criterion states that reaching a desired scientific conception requires the overcoming of competing misconceptions (Hammer, 1996). This interpretation regards misconceptions as something that can be substituted by other conceptions, hopefully desirable ones. It does not pay attention to the underlying cognitive processes but concentrates on the change in conceptions, rather than the process per se. This interpretation also permits the existence of so-called intermediate conceptions that are not accurate as such but might be helpful en route to scientific conceptions. Our use of the term follows this description. With this description in mind, the most essential misconceptions found in the literature are introduced in the following chapters.

A summary of accurate concept descriptions and a list of students' misconceptions concerning individual concepts are presented in Table 2.1. A large group of findings addresses students' problems in distinguishing between concepts: concepts and their characteristics are often paralleled or confused with each other. In addition, the dependencies for quantities are often misunderstood. Other problems are related to the nature of quantities: heat and work are often seen as state quantities rather than process quantities.

*Table 2.1. Concept descriptions and students' common misconceptions at upper secondary and university levels.*

| Accurate concept descriptions [A, B] | Students' misconceptions |
|---|---|
| *Temperature* | |
| • Measured with a thermometer<br>• A measure of the tendency to spontaneously give energy<br>• A measure of the average kinetic energy of particles | • Paralleled with heat<br>• Connection to thermal equilibrium is not understood<br>• Related to density<br>• Related to molecular collisions<br>• Temperature as a property of a substance [C, D, E, F, G, H] |
| *Pressure* | |
| • Force per area<br>• Caused by the collisions per time unit and area | • Connection to mechanical equilibrium is not understood<br>• Incorrect references to the motion of the particles<br>• Paralleled with particle density [F, H, I] |
| *Volume* | |
| • A measure of space occupied by the system | • Confused with the amount of gas<br>• Incorrectly related to the molecular size of gases<br>• Cooler gas takes less space<br>• Incorrect microscopic models [F, H, J] |
| *Heat* | |
| • Energy in transfer due to the temperature difference | • Paralleled with temperature<br>• Confused or paralleled with work/internal energy/thermal energy/enthalpy<br>• Generated in interactions between particles<br>• Considered as a substance [C, D, E, F, G, K, L, M, O] |
| *Work* | |
| • Energy in transfer not caused by temperature difference; an agent is required<br>• $\bar{F} \cdot \overline{dr}$ | • Confused or paralleled with heat and state quantities<br>• Direction of the work is misunderstood<br>• Considered to be path independent [E, K, L, M, O] |
| *Thermal energy/Internal energy* | |
| • The sum of microscopic kinetic and potential energies in a matter | • Confused with heat, work, enthalpy, and mechanical energy<br>• Can be changed via interactions within the system [K, M, P] |

[A] (Schroeder, 2000)
[B] (Knight, 2008)
[C] (Thomaz, Malaquias, Valente, & Antunes, 1995)
[D] (Barbera & Wieman, 2009)
[E] (Beall, 1994)
[F] (Kautz, Heron, Loverude, & McDermott, 2005a)
[G] (Kesidou & Duit, 1993)
[H] (Kautz, Heron, Shaffer, & McDermott, 2005b)
[I] (Rozier & Viennot, 1991)
[J] (Robertson & Shaffer, 2013)
[K] (Loverude, Kautz, & Heron, 2002)
[L] (Meltzer, 2004)
[M] (van Roon, van Sprang, & Verdonk, 1994)
[N] (Wiser & Tamer, 2001)
[O] (Goldring & Ogborn, 1994)
[P] (Thomas & Schwenz, 1998)

Many problems related to the laws, models, and processes of thermal physics are already covered in Table 2.1, but some of them require additional attention. With respect to the first law of thermodynamics, a relatively high number of misconceptions and other types of problems are observed amongst students. A profound finding is that students do not understand the relevance of a particular law, and so they use other, often inoperative, explanations instead. A typical example is students' excessive confidence in the ideal gas law in situations where it cannot offer an adequate explanation (Barbera & Wieman, 2009; Loverude et al., 2002). Understanding the impact of work on a system's internal energy has proven to be problematic for students, as is the concept of reversibility (Meltzer, 2004; Thomas & Schwenz, 1998). It has also been observed that the energy conservation law is sometimes understood in the sense that the energy of a system always remains constant (Thomas & Schwenz, 1998). When it comes to applying the law in physical situations, students seem to have great problems in using $pV$ diagrams as a problem-solving tool (Meltzer, 2004).

Some misconceptions and problems concerning the ideal gas law have also been observed. Students seem to have a tendency to ignore one of the quantities or they assume it to remain constant even if insufficient evidence is offered in support of this conclusion (Kautz et al., 2005a; Rozier & Viennot, 1991). The symmetry of conclusions drawn on the basis of the law is also problematic for students: they may understand how change in temperature affects volume but they do not understand this connection in reverse, for example (Rozier & Viennot, 1991). The substance-independence of the law also seems to be problematic for students (Kautz et al., 2005b).

The final group of misconceptions introduced is related to thermal processes. One typical misconception is related to the ways in which students confuse processes: heat is claimed to equal zero under isothermal conditions and temperature is claimed to stay constant during an adiabatic process (Kautz et al., 2005a; Loverude et al., 2002), or all expansion processes are considered to be isothermal (Beall, 1994). Students also have problems in understanding the physics of free expansion processes (Bucy, Thompson, & Mountcastle, 2005; Thomas & Schwenz, 1998). With regard to the multi-phase processes, heat and work are poorly understood in the context of ideal gas (Meltzer, 2004). Related to these processes is also students' tendency to consider the role of insulation as intended to keep temperature constant rather than preventing heat transfer (Kautz et al., 2005a; Loverude et al., 2002).

### 2.3 TEACHING INTERVENTIONS

The misconceptions and other problems presented above have inspired researchers and teachers to design various teaching methods and interventions to overcome these difficulties. This section provides a concise overview of teaching interventions in the context of higher education.

Physics education research groups in US universities have designed instructional materials under the title of *Tutorials in Introductory Physics* to help university students to comprehend significant concepts and to assist them in developing scientific reasoning skills. Tutorials designed to supplement lecture-based teaching consist of a pre-test, a worksheet, a homework assignment, and a post-test. The pre-test helps students and instructors to identify the level of their understanding. During the actual tutorial sessions, students follow the carefully structured worksheets in small groups. This includes discussions amongst themselves and with their instructors. The instructors' role is to ask questions that aim at helping help students to find their own answers. The homework expands on topics covered in the worksheets. The post-tests are used in course exams to address the same themes as those covered in the tutorial sessions. (McDermott & Shaffer, 2010)

One tutorial addressed the concepts of heat and temperature in order to reinforce students' scientific view of these topics (Cochran, 2005). It was observed that the tutorial helped students to make a distinction between heat and temperature.

However, after the tutorial the students still had problems in understanding thermal equilibrium and in applying the concepts of heat capacity and specific heat correctly. In consequence, it was decided that the tutorial required further development.

The first law and the concepts of heat, work, and internal energy have also been addressed in another tutorial (Barbera & Wieman, 2009). It had already been found in pre-testing that the concept of work was understood well and so emphasis was placed on the other two concepts. Students' understanding of heat and internal energy change was shown to improve significantly during the tutorial sessions. In comparison with the control group receiving traditional instruction, the tutorial group scored significantly ($p<0.01$) better in conceptual questions, while no difference was observed in the solving of numerical problems.

Another article evaluated changes in students' conceptions as a consequence of the tutorials concentrating on the first law of thermodynamics and the ideal gas law. Used as interactive lecture tutorials, both of these improved students' conceptual understanding compared with the control group receiving standard lecture instruction. Some students also carried out a tutorial laboratory experiment on the ideal gas law that also had a significant impact on their learning. A positive impact was observed both in students' correct multiple-choices and in their reasoning. (Kautz et al., 2005a)

Two other tutorials addressed the ideal gas law and microscopic processes. It was observed that students achieved a solid understanding of the substance-independence of the ideal gas law as a consequence of the tutorials. With respect to microscopic processes, students still experienced problems in understanding temperature on a microscopic level, but the tutorials helped them in distinguishing between the concepts of temperature and particle density (Kautz et al., 2005b).

There is also evidence of the impact of cognitive conflict-based instruction with pre-service primary school teachers (Baser, 2006). The instruction was based on the idea that the students were shown a phenomenon that conflicted with their current conceptions, and they were asked to discuss the phenomenon in small groups. Based on the results of Thermal Concept Evaluation (Yeo & Zadnik, 2001), the cognitive conflict-based instruction was significantly more effective than conventional lecture-based teaching in improving the students' understanding of heat and temperature. However, it was also found that some misconceptions originating from everyday life, e.g., understanding the role of thermal insulation, were shown to be difficult to change.

A detailed description of the ways in which high schools students' everyday life conceptions regarding heat underwent a change in the direction of the scientific conceptions is introduced in the article that draws on a teaching approach referred to as *metaconceptual teaching* (Wiser & Tamer, 2001). In practice, this meant that the existence of two conceptualizations, namely "everyday heat" and "science heat", was addressed explicitly in teaching that included experiments, analogies, and discussions. The approach was ultimately useful in distinguishing between the two conceptualizations, and students' learning was improved as a result of this type of teaching.

Interventions such as these have proven to be effective in improving students' conceptual understanding in the field of thermal physics. Such interventions may, however, require curriculum reform, teaching assistants, and other supplemental resources, but it must be acknowledged that the cost of the resources and training may well be beyond the reach of many institutions. In consequence, we hoped to devise a straightforward teaching intervention that could be applied by any lecturer who was aware of its potential.

# *3 Methodology, context, and sample*

This section concerns the methodology, context, and samples of the research. Firstly, the paradigm, the research design, and characteristics of the research strategy are introduced. Secondly, the context of the study is described. The third sub-section then concentrates on providing an overview of the data collection methods and analysis procedures.

## 3.1 PARADIGM, RESEARCH DESIGN, AND RESEARCH STRATEGIES

The paradigm underlying this research project is pragmatism. Characteristic of pragmatism is that it is not strictly committed to any specific philosophy but that it emphasizes the research problem, which can in turn be approached through the application of a variety of methods so that it can be properly understood (Creswell, 2009; Onwuegbuzie & Leech, 2005; Teddlie & Tashakkori, 2009). Hence, pragmatism offers a researcher freedom in choosing the research design, research strategies, and methods. Part of the pragmatic worldview is concerned with acknowledging that the research does not occur in isolation from the social, historical, or other contexts (Creswell, 2009), but that the impact of the context is dependent on the research topic itself.

When compared to other paradigms such as post-positivism and constructivism, pragmatism does not take a strong stand on ontological or epistemological issues. With respect to ontology, pragmatism permits both realistic and relativistic views of the nature of reality, and also perspectives that exist between the two views. In other words, the effective viewpoint depends on context. Typically, the viewpoint lies somewhere between the two poles, even if in most studies it is rarely addressed explicitly within the pragmatic paradigm. With respect to epistemology, pragmatism accepts both objective and subjective points of view, meaning that knowledge concerning reality can be absolute or dependent on the observer, or somewhere between these two. (Johnson & Onwuegbuzie, 2004; Maxcy, 2003; Teddlie & Tashakkori, 2009) In general, the nature of reality and knowledge are paid relatively little attention by pragmatic researchers because there is a tendency to use the best possible explanations within the current situation, and the viewpoints are used adaptably, depending on the research phase.

The philosophical issues introduced above offer the researcher an adequate amount of freedom in making choices regarding a research project in general.

In the present case, the core of pragmatism represents permission to apply any methods, worldviews, and assumptions that are needed in order to answer research questions thoroughly, as long as the choices made can be justified individually. Pragmatism suits our research well since it is our aim to acquire a wide and versatile view of the targets of our study, and it is considered that other paradigms would impose unnecessary limitations on this task.

The research design of this study relies on using mixed methods. This approach combines both qualitative and quantitative methods in data-collecting and -analysis (Creswell, 2009; Teddlie & Tashakkori, 2009). We refer to the term research design, although some authors have claimed that it is, rather, a research paradigm or simply a methodological choice (Greene, 2008; Johnson & Onwuegbuzie, 2004; Teddlie & Tashakkori, 2009). However, in our usage it includes all of the major decisions, ranging from broad assumptions to practical issues. Thus, referring to research design appears to be the most appropriate choice (Creswell, 2009).

It has been claimed that mixed methods can help a researcher to understand certain phenomena better than quantitative or qualitative methods alone (Howe, 1988; Gorard & Taylor, 2004;

Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005). Mixed methods permit the researcher to address confirmatory and exploratory questions concurrently. Hence, theory can be both generated and verified in mixed methods research. (Teddlie & Tashakkori, 2009) Moreover, using mixed methods can provide stronger inferences basing on qualitative and quantitative data, and in this way a more comprehensive view can be obtained (Creswell, 2009; Teddlie & Tashakkori, 2009). The possibility of divergent conclusions emerging from divergent qualitative and quantitative components can also be interpreted as valuable. It provides an opportunity to develop more robust explanations for a particular phenomenon or alternatively it can reflect different perspectives on the phenomenon per se. (Teddlie & Tashakkori, 2009)

With respect to the research strategy guiding the specific research procedures, this research project bears the characteristics of two mixed methods strategies: concurrent triangulation on the one hand, and concurrent embedded strategies on the other. Concurrency means that quantitative and qualitative data can be collected in parallel, with one data set not affecting the collection of the other. In the triangulation design, different types of data sets are used to support each other when the embedded design is based on finding information at different levels or on answering different research questions. (Creswell, 2009; Johnson & Christensen, 2008) Individual research phases may include characteristics acquired using various research strategies: parts relying on quantitative data follow the strategies of survey research or experimental research, while qualitative parts possess the properties of a case study and design-based research, depending on the research phase (Creswell, 2009; Gorard & Taylor, 2004; Johnson & Christensen, 2008).

### 3.2 CONTEXT

All of the data collection took place in the context of introductory courses on thermal physics at the University of Eastern Finland. The data was collected in three different courses: Thermal Physics and Basic Physics II on the Joensuu campus and Basic Physics IV on the Kuopio campus. Collecting data in the context of two different courses on the Joensuu campus was motivated by a curriculum reform that occurred during the research project: the courses in question were those where students faced thermal physics content for the first time in their university studies.

All of these courses can be considered to be somewhat similar with respect to preceding studies at the lower and upper secondary level of education. A majority of the students had taken a course in thermal physics at upper secondary school, but we do not have the precise percentages for all the sub-groups. For the known sub-groups the percentages varied between 69% and 94%.

All of the courses were designed for physics majors and also minors. The numbers of participants varied between 40 and 120, depending on the course. The Basic Physics II course had a significantly larger number of participants than the other two courses. The exact sample sizes in the different phases of the research are presented in section 3.3.1. The cohorts on the Joensuu campus consisted of students majoring in mathematics, physics, chemistry, and computer science. Both teachers and scientists are educated on the Joensuu campus. On the Kuopio campus, the students were majoring in physics, science and technology, bioscience, and computer science.

There was some variation in content between the courses but the essential topics related to the present study were covered to an equivalent extent. A variety of textbooks were used as course materials, but no significant differences were observed in the content or approaches (Knight, 2008; Schroeder, 2000; Young & Freedman, 2004)

Teaching on the courses was conducted by means of lectures and homework sessions. Participation in both the lectures and the homework sessions was voluntary for the students: typically, attendance percentages varied between 50% and 70%, with slightly larger numbers completing the home assignments than those that attended the lectures.

The lectures were conducted in 2×45 min periods, two or three times a week, depending on the course. In the following week, the lectures were supplemented with homework sessions addressing the same themes. There was also a weekly time reserved for the homework sessions, also consisting of 2×45 min. In these sessions the students presented their solutions to the homework exercises that they had been given the previous week. When necessary, a teaching assistant commented on and corrected the students' solutions. At the end of the courses, an exam was also held. The course grade was determined by points from the exam supplemented with extra points received from the homework sessions, supplementing the course exam by, at most, 10% of the maximum points obtainable in the exam itself.

Typically, covering the thermal physics content under inspection in this study took approximately 12×45 min of lectures and 6×45 min of homework sessions. With respect to the Basic Physics IV course held on the Kuopio campus, we have no precise information about the time allocation, but we assume that it basically matched the time allocation accorded the courses on the Joensuu campus.

### 3.3 DATA COLLECTION AND ANALYSIS METHODS

This section introduces the data collection and analysis methods used with respect to articles I-V. Firstly, the use of questionnaires and analysis of the data acquired is discussed. Secondly, the implementation and analysis of semi-structured interviews is presented, followed by a description of the use of the audio recordings.

### 3.3.1 Questionnaires

Using questionnaires enables the researcher to reach a large number of respondents in a time- and cost-efficient way. In comparison with interviews, standardized questions fade out potential interpretations or distortions caused by an individual researcher. In order to achieve these aims, the wording and purpose of a questionnaire has to be carefully evaluated, perhaps piloted. (Bryman, 2012; Munn & Drever, 1995; Teddlie & Tashakkori, 2009)

In the course of the present research, use was made of questionnaires in order to acquire comprehensive data that would concern the whole cohort under inspection. The data collection itself was performed by using paper and pencil tests at all stages of the research project. In consequence, the results obtained by this means can be found in all of the research articles numbered I-V.

The questionnaires based on the test questions were either designed by physics education research groups at US universities (Loverude et al., 2002; Meltzer, 2004), to Finnish Matriculation Examination (FMEB, 2011) or they were constructed independently based on the previous research findings discussed in section 2.2, above. With regard to the design process of the self-constructed questionnaires, several cycles of reading, evaluation, and reorganizing were conducted inside the research group, and exterior evaluation was also utilized. The use made of the questionnaires in the research articles can be seen in Table 3.1. The questionnaires themselves can be found in articles I, II, and V, and also from the original sources (FMEB, 2012; Loverude et al., 2002; Meltzer, 2004).

With regard to the student samples, the data was collected in several stages from the participants in three different courses on the two campuses at the University of Eastern Finland. A stronger emphasis was placed on the Thermal Physics and Basic Physics II courses implemented in Joensuu, while the Basic Physics IV course on the Kuopio campus played a supportive role.

*Table 3.1.* *The use of the questionnaires in articles I-V.*

| Questionnaire<br><br>Article | Loverude et al. 2002 | Meltzer, 2004 | FMEB, 2011 | Self-constructed |
|---|---|---|---|---|
| I (Eur. J. Phys.) | X | | | X |
| II (Res. Sci. Ed.) | X | | | |
| III (GIREP 2010) | | X | | |
| IV (GIREP 2011) | | X | | |
| V (PRST-PER) | | X | X | X |

The numbers of students participating in the different stages of the data collection in the courses are shown in Table 3.2, together with the references to articles I-V in which the samples have been discussed.

*Table 3.2.* *The numbers of students, course by course, in the different stages of the data collection. The sample sizes varied depending on the stage of the course. In consequence, these are shown separately for the courses where data was collected more than once. The column "Articles" refers to the articles where the corresponding sample is under evaluation. Pre = pre-testing, Int = Intermediate testing, Post = Post-testing.*

| Course and year | Sample size, N | Phase of the course | Article |
|---|---|---|---|
| Thermal physics, 2007 | 48 | Pre | I |
| Thermal physics, 2008 | 45 | Int | III |
| Thermal physics, 2009 | 38 | Pre | I+II |
| Thermal physics, 2009 | 31 | Int | III |
| Basic Physics IV, 2010[A] | 35 | Int | III |
| Basic Physics II, 2010 | 69 | Int | IV |
| Thermal Physics, 2011 | 31 | Int | IV |
| Basic Physics II, 2011 | 75 | Pre | V |
| Basic Physics II, 2011 | 65 | Int | V |
| Basic Physics II, 2011 | 65 | Post | V |

[A] This course was held on the Kuopio campus.

Analyzing the data collected with the questionnaires followed the same protocol in articles I, II, III, and V. The questionnaires were intended to elicit a comprehensive view of the conceptions held by the whole cohort, and hence the typical basics of content analysis were applied. The key feature of the content analysis is that it is used to reduce the texts, which frequently consist of lengthy responses and are hence rather complicated, into simpler categories (Burnard, 1996; Elo & Kyngäs, 2008; Weber, 1990). Reduction of this kind has made it possible to quantify the qualitative data in the sense that the descriptive nature of the data has been maintained at a reasonable level (Krippendorff, 2004; Tuomi & Sarajärvi, 2002).

In the present analysis we aimed at categorizing students' open responses or explanations based on the conceptions observed in these responses. Hence, the basic unit of analysis was *a conception* that may have been expressed to varying degrees by the individual students (Elo & Kyngäs, 2008). This means that the analysis was not restricted to individual words or sentences; rather, we aimed at accessing the students' conceptions, regardless of the form in which they were expressed – an equation, a single word, or a paragraph can all refer to the same conception. The conceptions may be scientifically accurate or inaccurate. In the latter case they are referred as misconceptions. Hence, defining the unit was based on a categorical distinction (Krippendorff, 2004). If more than one conception was observed in a response, we utilized categorization systems that enabled the conceptions to be categorized under more than one category simultaneously.

The analysis process was made up of a combination of data-driven and theory-driven processes. Owing to the relatively large amount of previous research available, the theory-driven process received greater emphasis. This means that earlier research findings (see the literature review in section 2.2) served as a starting point for formulating the categories. (Elo & Kyngäs, 2008; Hsieh & Shannon, 2005; Mayring, 2000; Tuomi & Sarajärvi, 2002).

It should be noted, however, that not all of the conceptions observed in the students' responses could be matched with the categories derived from the theory. In addition, some of these categories turned out to possess interesting sub-structures that could be specified. These types of responses were categorized by following the general principles of data-driven content analysis process (Elo & Kyngäs, 2008; Hsieh & Shannon, 2005). This process consisted of reading the responses, looking for similarities and dissimilarities, and comparing the findings to the theory-driven categories in order to avoid overlapping. (Elo & Kyngäs, 2008; Mayring, 2000; Tuomi & Sarajärvi, 2002) If a new category was formulated, the data that had already been categorized was re-evaluated. Hence, several cycles of reading and organizing the data took place during the categorization stage.

With regard to article IV, the data analysis process was more straightforward because the results consisted of the proportions of students' correct choices in multiple choice tests. Thus, the analysis consisted simply of calculating the numbers of correct choices that could be achieved with correct responses. In this case, it follows that the results in this particular article are more declaratory in nature than descriptive.

In order to support our descriptive results, in article V we supplemented our analysis with statistical tools. We utilized McNemar's test to evaluate the statistical significance of the changes observed when students' explanations were categorized as either accurate or inaccurate. Thus, each response that differed from the desired one was categorized as inaccurate. The procedure started with the calculation of the number of explanations that had been changed from correct to incorrect ($x$) and vice versa ($y$). Next, the $X^2$-values were calculated with the aid of equation 3.1, which follows the shape of the $X^2$-distribution with one degree of freedom

$$X^2 = \frac{(x-y)^2}{x+y}. \quad (3.1)$$

Later, the $X^2$-values were converted to $p$-values. Any changes were considered to be statistically significant if their $p$-values were smaller than 0.05 (Durkalski, Palesch, Lipsitz, & Rust, 2003).

### 3.3.2 Interviews

To obtain detailed information about the students' ideas and conceptions, in article II semi-structured interviews were utilized as a data collection method (Gillham, 2005; Kvale, 1996; Patton, 2002; Teddlie & Tashakkori, 2003). The method is described as a flexible, yet relatively structured, way to produce data of high quality. There may, nevertheless, be a number of disadvantages associated with semi-structured interviews, including the amount of preparation, potentially high costs, and difficulties concerning the interpretation and presentation of the material (Bryman, 2012; Gillham, 2005; Kvale, 1996). The method is indeed relatively laborious and time-consuming, but it also provides rich and detailed data in an adequately flexible manner.

Characteristic of the semi-structured interviews is that the same themes are addressed in all of the interviews, but exactly the same protocol is not necessarily followed at all times. Although some kind of interview frame has often been used, follow-up questions outside the interview frame may also have been asked in order to probe an interviewee's ideas furthermore. This aspect required the interviewer to be well-prepared and familiar with the themes addressed. (Gillham, 2005)

With respect to the interviewees, they were chosen based on their answers in the pre-test. Our aim was to obtain versatile data about students' conceptions and reasoning, and so we selected students who had provided either good, average, or modest answers in the pre-test (Stake, 1995; Weiss, 1994). One criterion for choosing the interviewed students emerged from our experience with Finnish students: we chose students whose written answers in the pre-test were adequate in length since reticent writers often prove to be also reticent speakers. In total, five students with answers of different levels of accuracy were interviewed.

All of the interviewees had taken a course in thermal physics at upper secondary school. Four of them were physics majors, while of them was a mathematics major. In the course of the analysis, one of the interviewees was omitted from the analysis because of the similarities between her responses and those provided by other interviewees.

The interview frame was designed on the basis of the questionnaire that had been used (Loverude et al., 2002). The aim of the interviews was to obtain detailed data concerning each interviewee's conceptions and reasoning, and the themes addressed in the questionnaire provided an appropriate context. The interview frame was designed in cooperation with the supervisors so as to ensure that the essential themes would be addressed. Examples of the interview questions are provided in appendix B of article II.

The interviews began by asking students to explain in detail their written answers in the preceding questionnaire. The interviewer then concentrated on asking additional questions concerning the principles used in the students' reasoning, the meanings of concepts, alternative ways of explaining the phenomena, and microscopic level explanations. Follow-up questions were also posed whenever the interviewer considered it necessary. The lengths of the interviews varied between 30 minutes and an hour. The students were encouraged to express their ideas freely, and prompts were avoided as much as possible. The interviewer did not comment on students' responses so that interviewees' ideas could be observed with as little as possible input from any other individual. Thus, no teaching occurred during the interviews per se.

The basics of data-driven content analysis were utilized in analyzing the interviews (Elo & Kyngäs, 2008; Krippendorff, 2004; Tuomi & Sarajärvi, 2002). The process began by transcriptions being made of the interviews. Irrelevant interjections were omitted, but otherwise the transcription process provided word-by-word texts where the exact phrases used were preserved. The next stage of the analysis focused on finding text fragments that revealed something of interest in the interviewees' thinking concerning the themes addressed in article II. The text was then translated into English and edited to provide a readable manuscript. The conclusions were drawn up on the basis of the first versions of the transcriptions so that the translation and stylization processes had no effect on the researchers' interpretations. (Tuomi & Sarajärvi, 2002)

### 3.3.3 Audio recordings

During the final phase of the intervention presented in section 4, recordings were made of peer discussions. Audio recording is a reliable way of collecting detailed and exact data from discussions and interviews. (Bloor & Wood, 2006) In our use, the purpose of the audio recordings was to reveal the various kinds of discussion that students produced when asked to compare the answers they had individually given earlier. In order to record such peer discussions as authentically as possible, the students were given no instructions and they were expected to discuss the topics as naturally as they would without a recorder. The selection of the recorded pairs was random and voluntary. The lecturer implementing the intervention would casually enter the lecture hall and simply asked the students which pairs would like to participate in audio recordings. From the voluntary pairs, the lecturer then selected five pairs who were considered by the lecturer to be generally talkative enough.

In general, analyzing the audio recordings followed the normal procedure for data-driven content analysis (Tuomi & Sarajärvi, 2002). The analysis began with the transcription process. The discussions addressed seven questions posed in a diagnostic test (Meltzer, 2004), and hence all of the transcripts were divided into seven parts based on the tasks that students had discussed. Our aim was to find versatile examples of the impact of the discussions on the students' final answers. Thus, all of the discussions were analyzed, task by task, to find the most interesting extracts that would illustrate the various types of discussions that the students had engaged in. After we had selected the extracts and drawing conclusions from them, the quotations were translated into English and edited for brevity and readability.

# 4 The intervention

## 4.1 DESIGNING THE INTERVENTION

To enhance students' learning and to address their misconceptions, which have become familiar from the literature and our own research, we designed a teaching intervention. The following principles guided the design process:

- In order to enhance students' conceptual understanding, the most common misconceptions reported from previous research are addressed in the intervention.
- Preparing and executing the intervention has to be relatively straightforward so it will not burden the lecturer to any greater extent than would the preparation of a conventional lecture or exam.
- The intervention needs to be executed in a lecture-setting with no special resources, training, or assistants.

The design and implementation of the intervention is described in the following sections. A theoretical base relying on scaffolding in the form of content hints and peer interaction precedes the description of the actual implementation of the intervention.

### 4.1.1 Scaffolding

The theoretical framework of the intervention is based on Vygotsky's theory of the zone of proximal development (ZPD) and on scaffolding (Chaiklin, 2003; Vygotsky, 1978). Vygotsky's studies concentrate on young children but his theories have also been applied to older learners (Hansman, 2001). The essential idea underlying ZPD is that succeeding in a task can occur in two ways: either individually or with some kind of guidance or assistance. The zone in which the latter takes place is termed the ZPD: a learner can succeed in an otherwise unachievable task when guided by a more knowledgeable person or when aided

in some other way. When a learner masters a topic, a part of the ZPD has become part of the zone within which the learner can succeed independently.
Scaffolding utilizes the idea of ZPD so that a minimum amount of help required to succeed in a learning task is brought into the ZPD of the learner (Collins, Brown, & Newman, 1989). Originally, the term scaffolding was reserved for situations where the help was offered to an individual learner by a formal instructor (Wood, Bruner, & Ross, 1976). However, the meaning of the concept has been widened to cover help offered for a larger group simultaneously, and also as help provided by peers (Ge & Land, 2003; Greening, 1998; Jones & Carter, 1998). In the present research, the term is used in this wider sense, which includes help provided by an instructor or peers to other individuals or to a larger group of learners as a whole.
Concrete results concerned with the benefits of scaffolding in the learning of physics are somewhat difficult to find, especially when with respect to university-level education. In most cases, the results are general in nature rather than related strictly to the content (Palinscar & Brown, 1984; Puntambekar & Hübscher, 2005; Wood et al., 1976). Examples of the findings from various disciplines include:

- Students' comprehension has improved significantly (Palinscar & Brown, 1984).
- The change in students' comprehension has been long-lasting (Palinscar & Brown, 1984).
- Multiple forms of scaffolding are more helpful for students that just one form (Puntambekar & Kolodner, 2005).
- Scaffolding has helped students in understanding the hierarchical structure of physics (Lindstrøm & Sharma, 2009).

However, these results are not necessarily helpful when making predictions or hypotheses since scaffolding in its broad meaning is not an unambiguous concept: it can take a number of different forms.

In our usage, scaffolding can be implemented in two ways. Firstly, students are offered content hints concerning the content taught in lectures and homework sessions. Secondly, peer interaction is utilized as another way to improve students' learning. Details of these two areas are presented in the following sections.

### 4.1.2 Hints

In a learner-instructor interaction content hints can be used to guide a learner along a learning pathway (Chi, 1996; Zhou et al., 1999), and as a result of the teacher's expertise this is often done spontaneously, and with no prior planning. With respect to the larger group of learners, providing hints is limited by the instructor's restricted opportunities for probing the students' actual need for such hints.

There are various computer-based tutoring systems in different areas of the natural sciences that offer students hints on demand when solving problems (Gertner & VanLehn, 2000; Knight, 2013; Koedinger & Corbett, 2005; VanLehn et al., 2005). It has been demonstrated that students' learning and motivation can be improved with the aid of such systems (Koedinger & Corbett, 2005; VanLehn et al., 2005). These kinds of intelligent systems facilitate fairly individualized hints, but it has also been claimed that the kind of learning outcome that can be achieved with the help of human tutors cannot be achieved so successfully with computer-aided systems (Koedinger & Corbett, 2005).

Apart from study of the content hints offered by computer-aided systems, the amount of actual research related to providing content hints seems to be sparse, if not entirely absent. Other types of hinting, meta-cognitive question prompts and self-reflection prompts, have also been evaluated in the literature, to name only one or two examples (Ge & Land, 2003; Davis, 2000). For some inexplicable reason, the use of the most obvious type of hinting, straightforward content hints, seems to have been ignored in research reports, probably because of the lack of novelty or originality value. However, content hinting can be conducted without providing students with any direct

answers, and so there is no good reason for excluding the evaluation of this kind of intervention from the research.
Because of the limitations imposed by the lecture environment, it is not our aim to offer individualized hints. Rather, we would wish to offer hints to a whole cohort in parallel, and the individual learner's responsibility is to evaluate the necessity of the hints. This approach can be executed by providing the whole student cohort with hints about the physics content taught in earlier lectures and homework sessions: the role of the hints is to help the students to apply the content already taught rather than teaching them something new.

### 4.1.3 Peer interaction

The benefits of peer interaction and peer discussions are widely acknowledged in the field of learning science (Alexopoulou & Driver, 1996; Crouch & Mazur, 2001; Jones & Carter, 1998). Peer interaction can occur in various ways, but the common characteristic is that learners discuss with each other as a part of the learning process, in groups of varying sizes (Cooper & Robinson, 2000).
Previous research has shown that peer interaction can improve students' learning significantly, at both conceptual and quantitative problem-solving levels (Alexopoulou & Driver, 1996; Crouch & Mazur, 2001; Rao & DiCarlo, 2000). Students and teachers also seem to acknowledge the value of peer interaction in engaging students and improving their conceptual understanding (Gunstone, McKittrick, & Mulhall, 1999). Moreover, the use of peer interaction seems to reduce the student attrition: the drop-out rates from courses utilizing peer interaction were significantly lower than for conventional courses (Lasry, Mazur, & Watkins, 2008).
With respect to the efficient use of peer interaction, it has been suggested that the impact of peer interaction is greatest when approximately half of the students have accurate conceptions prior to the start of the interaction phase (Crouch & Mazur, 2001). With respect to individual learners, it has been shown that students with both lower and higher background

knowledge can benefit from peer interaction (Lasry et al., 2008). Peer interaction seems to have a positive impact on learning, although the effective size varies depending on the background knowledge of the whole cohort and also that of individual students.
In the case of our intervention students were required to discuss in pairs as the final stage of the intervention. They were permitted to choose pairs freely because of the advantages this free choice may possess (Alexopoulou & Driver, 1996). The reason for implementing discussions in pairs rather than in groups of three of four individuals was due to the limitations imposed by the lecture environment: discussions with more than two persons are more difficult to stage in a lecture hall, even if it has been suggested that larger groups could produce better learning outcomes (Alexopoulou & Driver, 1996; Gunstone et al., 1999).

### 4.2 IMPLEMENTING THE INTERVENTION

The intervention was implemented in a lecture hall during the normal lecture-time. The students were informed about the intervention beforehand, and enrolment was rewarded with a few extra points with regard to the course evaluation. Enrolment in the intervention was slightly larger than for ordinary lectures, although both were voluntary as far as the students were concerned.
A diagnostic test related to the multi-phased process of an ideal gas was utilized in the intervention, both as teaching and as test material (Meltzer, 2004). The test was modified slightly to suit the way in which we presented the first law of thermodynamics in the course: we inquired about work done on the gas rather than work done by the gas. To succeed in the test, students needed to be familiar with the following concepts, principles, and phenomena: work, heat, internal energy, the kinetic energy of particles, the first law of thermodynamics, the connection between thermal energy and temperature, and thermal

processes. This content was addressed in the lectures and homework sessions preceding the intervention.

The procedure and approximate time allocation for the intervention labeled as HPIL teaching (Hints and Peer Interaction in Lectures) is shown in Table 4.1. In the pilot study, the hinting phase included one further phase and hence the intervention took approximately ten minutes longer. In total, implementing the intervention took no longer than one hour.

***Table 4.1***. *The procedure and time allocation of the HPIL teaching intervention.*

| The intervention phase | | Approximate duration (min) |
|---|---|---|
| 1. | Individual working | 25 |
| 2. | Hinting phase A | 8 |
| | Hinting phase B | 8 |
| 3. | Peer interaction phase | 10-15 |

Data was collected after each phase, four times in total. This was done with the aid of four separate answer sheets. The tasks were handed out on separate sheets that were also returned to the instructor without further markings.

Initially, the students took the diagnostic test individually. This phase was used to encourage the students to apply the content they had learned in the lectures and homework sessions. With respect to results, this phase revealed the level of the students' conceptual understanding after receiving conventional teaching.

The second phase, consisting of two hinting phases, A and B, was designed to reveal whether hints related to physics content can improve students' conceptual understanding. The basis for the hints relied on previous findings related to students' misconceptions, as introduced in section 2.2. The hints and the corresponding misconceptions found in the literature are presented in Table 4.2. The hints are divided into two groups, A and B, due to the different nature of the hints, and they are also executed as separate parts in the course of the intervention.

*Table 4.2.* *Hints offered for students with the corresponding misconceptions familiar from previous research.*

| | Hint | Misconception to overcome |
|---|---|---|
| A. | Present three phases of the process on a $pV$ diagram | Work and heat during a cyclic process |
| B. | The internal energy of a system may change if a system and an environment exchange energy as heat $Q$ or work $W$: $\Delta U = Q + W$ | Problems in applying the first law |
| | The thermal energy of a monatomic gas is directly proportional to temperature $E_{th} = \frac{3}{2}nRT$ | A problem with the relationship between temperature and thermal energy |
| | The temperature of a gas describes the average kinetic energy of the molecules. $e_{avg} = \frac{1}{2}m(v_{rms})^2 = \frac{3}{2}k_bT$ | A problem with the relationship between temperature and the kinetic energy of particles |
| | Heat $Q$ is the energy transferred between a system and the environment due to a temperature difference. | Heat as energy in transit |
| | Work $W$ is the energy transferred between a system and an environment due to a mechanical interaction. | Work as an energy transfer mechanism |

The first hint requesting students to draw a $pV$ diagram aimed at helping students to understand that work and heat depend on the path that a process takes. The latter set of hints consisted of definitions or descriptions of the concepts and the relationships for those. These aimed at activating students to compare their current conceptions to the desired conceptions that they were offered. Moreover, this set of definitions and descriptions provides students with the pieces of content necessary for understanding and explaining thermal processes in a consistent and holistic manner when they are used concurrently.

The last stage of the intervention was a peer interaction phase. The students were asked to compare their answers and to discuss them in pairs. Finally, they were asked to write their consensus views of the tasks on an answer sheet. The duration of this phase varied because the students were free to leave once the tasks had been completed.

# 5 Results

The main results obtained in articles I-V are presented briefly in the following sections. The results are introduced thematically so the structure of this section follows the logic of sub-aims *i-iii*. Section 5.1 is based on articles I, II, and V, while section 5.2 is based on articles III, IV, and V. The findings presented in articles IV and V are presented in section 5.3.

## 5.1 STUDENTS' CONCEPTIONS AND REASONING PRIOR TO INSTRUCTION

Sub-aim *i* was formulated to figure out and describe students' conceptions and reasoning concerning thermal physics prior to instruction. This aim was pursued in articles I and II, and also in some parts of article V.

In the course of article I, students' conceptions were investigated with the aid of questionnaires, focusing on students' concept descriptions and ideas concerning the adiabatic compression process (Loverude et al., 2002). Students' explanations and reasoning concerning the same process were evaluated more profoundly in article II, for which questionnaires were supplemented with semi-structured interviews. Article V addressed students' concept descriptions and their ability to recognize thermal processes and to utilize $pV$ diagrams (FMEB, 2011).

The results showed that students' conceptions preceding their university studies were often inaccurate. With respect to the concepts of temperature, thermal energy, internal energy, heat, and work, various misconceptions were observed among the cohort. These concepts were often paralleled rather than distinguished between. In addition, the students had a tendency to use microscopic models to describe concepts, but these were often ambiguous as a result of flawed and unclear use of terms. Another relatively common feature in students' responses was the use of phrases based on everyday colloquial usage and on the appearance of the term, even if these were naïve or inaccurate. A tendency to concentrate on individual phenomena or equations rather than more general ideas was also observed in students' responses. Work, however, was described with relative accuracy in terms of mechanics, largely as a result of the students' previous university studies. In sum, it could be concluded that previous secondary level studies have not been able to provide students with an accurate understanding of the essential concepts of thermal physics.

In order to address students' abilities to apply the first law of thermodynamics, which is an essential content of physics learning at Finnish upper secondary schools (NBE, 2003), we also asked students to predict what would happen to the temperature of the insulated gas system when compressed (Loverude et al., 2002). The questionnaires revealed that a great majority of the students had no adequate understanding of the first law of thermodynamics: fewer than 10% of the students could use this law in their explanations of the phenomenon. As with the concept definitions, students often relied on microscopic models when explaining adiabatic compression, but only a minority of the students referred accurately to kinetic energy or the velocity of particles. Another common error was students' excessive confidence in the ideal gas law even though it would not offer an adequate explanation for the phenomenon. Connections between quantities, usually between temperature, volume, and pressure, also caused problems for students: a great number of them ignored some essential factors or found inaccurate dependencies.

In addition, it was observed that students' conceptions were context-dependent when their temperature descriptions were mirrored by their explanations in the adiabatic compression task. Students' concept descriptions were quite often in conflict with those that they had used in the adiabatic compression task. A similar phenomenon was observed in the interviews, where students tended to use various contradictory explanations. The interviews also revealed that students possessed a variety of different mental models, but they did not necessarily put them all on paper. Hence, during the interviews both accurate and inaccurate descriptions of the situation were revealed, but the interviewees were frequently unable to assess the operability of such descriptions, as could be seen in the flawed reasoning that ended up on paper.

A task addressing students' familiarity with heat-absorbing isochoric, isobaric, and isothermal processes and $pV$ diagrams revealed a significant gap in their pre-knowledge: only 36% of them made relevant attempts with respect to this task. Depending on the process, between 19% and 27% of the students drew correctly-shaped diagrams, but the direction of the heat-absorbing process was absent or incorrect in more than half of these. The isothermal process was the most problematic, with only 4% of the students drawing an acceptable diagram. 15% of the students drew a straight line with an ascending trend, suggesting that they considered pressure and volume to be directly proportional. These results indicate that students have major difficulties with the essential terminology and/or phenomena of thermal physics at the start of their university studies.

## 5.2 STUDENTS' CONCEPTIONS AFTER CONVENTIONAL TEACHING

The second sub-aim *ii* was formulated to address students' conceptions after they had received conventional university-level teaching consisting of lectures and homework sessions. This topic is dealt with in article III and also partly in articles IV and V. The emphasis in this section is on the results of article III, whilst the results of the other two articles play largely a supportive role as a consequence due of the different categorizations used.

The students' conceptions were evaluated by means of a diagnostic test describing the multi-phase process of an ideal gas (Meltzer, 2004). Seven multiple-choice tasks were used to discover the topics that students faced problems with, while a more thorough description of their conceptions was obtained by analyzing their explanations for these tasks.

The findings reveal that conventional teaching consisting of lectures and homework sessions left students with various misconceptions. The proportions of correct explanations varied between 10% and 62%, depending on the theme and the data collection year.

The most common misconception was the notion that heat or work equals zero in a cyclic process: approximately half of the students harbored either one or both of these misconceptions. This indicates that students have not grasped the meaning of process quantities even if some of the other tasks signaled the opposite.

More than one fourth of the students faced problems with the following topics: the impact of work on internal energy, understanding the concept of energy in general, distinguishing isothermal and adiabatic processes, and understanding the dependencies for quantities. For example, the kinetic energy of particles was often paralleled with pressure or volume instead of temperature, and it was claimed that heat and temperature were also directly proportional in the case of the isothermal process.

The following misconceptions with smaller proportions were also observed: heat and work were not distinguished, the direction of work was misunderstood, the definition for heat was misused, and students focused only on the some part of the process even though they had been asked to evaluate a whole process.

One typical problem, although not precisely involving a conception, was an almost complete inability to use $pV$ diagrams as a problem-solving tool. Considering the substantial use of these diagrams during the preceding teaching, this was a surprising result, indicating that the students had not grasped the value of *pV* diagrams during the conventional teaching that they had received.

These observations clearly revealed that conventional teaching has its weaknesses with respect to improving students' conceptual understanding, and this would evidently need to be enhanced in one way or another.

## 5.3 STUDENTS' CONCEPTIONS DURING AND AFTER THE INTERVENTION

Sub-aim *iii* was formulated to reveal students' conceptions during and after the HPIL teaching intervention, which had been designed precisely to overcome their misconceptions. Article IV concentrates on revealing changes in the number of correct selections made by students in the multiple-choice questions, while article V also evaluates changes in students' conceptions more profoundly. The results in articles IV and V concerned with multiple-choice selections are combined in the following sections. Section 5.3.1 shows the impact of intervention phases, while section 5.3.2 is devoted to introducing changes in students' conceptions per se. Section 5.3.3 introduces students' conceptions in the post-testing phase, namely the course exam, compared with the conceptions observed at the end of the intervention.

### 5.3.1 The impact of the individual intervention phases

The intervention consisted of four phases: the individual working phase, the two hinting phases A and B, and the peer interaction phase. In this section we evaluate the extent to which students' conceptions changed during the hinting and peer interaction phases.

The hinting phase A of the intervention, a request to draw a *pV* diagram, was designed to help students to realize possible flaws in their answers in the task concerning work in a cyclic process. With respect to this task, the percentage of students' accurate explanations increased and the percentages of misconceptions declined, a change that was statistically significant ($p = 0.03$), based on McNemar's test. Changes in other tasks were absent or statistically insignificant. Students' correct multiple-choices followed a similar pattern, while the changes were only minor in the case of the other tasks in comparison to that first mentioned, where it was 7 percentage points, which is in good agreement with the percentages of students' accurate explanations.

With respect to hinting phase B, which consisted of content hints, some changes were observed in the students' explanations. The percentages of accurate conceptions increased in most of the tasks during this intervention phase, the change varying greatly depending on the theme. One of the changes that was statistically significant ($p = 0.03$) in a task was that addressing a change in the kinetic energy of particles in an isothermal process. This confirms that the impact of content hints is dependent on the themes addressed. This was also seen in the percentages of correct multiple-choice selections, where changes varied between -5 and +11 percentage points, depending on the theme. The largest increase was observed in the task, mentioned above, concerned with the kinetic energy of particles in an isothermal process.

The last phase of the intervention, peer interaction, ended up being the most effective one in terms of the increase that it produced in the number of correct explanations. The change in the accurate explanations varied between -7 and +23 percentage points during the peer interaction phase: the decrease of 7 percentage points was observed in the task concerning heat in an isothermal process. Changes were statistically significant ($0.0001 < p < 0.02$) in all but one of the tasks, with a negative impact concerning a task addressing heat in an isothermal process ($p = 0.03$). With respect to the students' correct multiple-choices, changes varied between -5 and +15 percentage points, the average being +8 percentage points.

The audio data collected during the peer interaction phase provided valuable examples of the discussions that students conducted. Students with inaccurate explanations were often willing to modify their conceptions if the discussant had good arguments in support of an accurate conception. However, we also witnessed a peer discussion where an individual with an accurate conception was uncertain about her own explanation and so she was persuaded to switch to the wrong one because she was unable to find any flaw in the alternative explanation. In addition to these observations, it was noted that if both discussants possessed inaccurate conceptions, their ability to reach the right explanation was unlikely because their discussion was unable to challenge their fallacious conceptions. These are, however, individual examples taken from the discussions, and no generalizations can be based on them. Nevertheless, they provide an interesting view of the kind of discussions that students may conduct. It can also be claimed that, together with other data sets, they form an entity that is both generalizable and detailed.

The intervention examined as a whole proved to be an effective way to enhance students' learning. The increase in students' correct explanations was statistically significant ($0.00002 < p < 0.02$) in all but two[2] tasks. The peer discussion phase was the most effective part of the intervention, but other phases also had a significant effect, and hence we conclude the intervention to be functional in its current form.

### 5.3.2 A summary of changes in students' conceptions

In total, students' explanations were placed in 45 categories in the seven tasks of the intervention. Seven of these were accurate, but another 38 categories referred to students' misconceptions, their combinations, or blank and uncategorized responses. Hence, the present section focuses on introducing changes in accurate conceptions and in the most prevalent misconceptions and uncategorized explanations with percentages greater than 15%. This is an arbitrary limit set to summarize the most

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[2] If looser criteria are applied to the explanations in the task addressing the heat in an isochoric process, change becomes statistically significant in all but one task; this is explained in greater depth in section 5.3.2.

interesting findings rather than repeating the full results of article V.

When asked about the work in an isobaric expansion process, students' accurate conceptions increased from 52% to 80%. Two prevalent misconceptions, the confusion of heat and work and misunderstanding the direction of work, were effectively overcome by the intervention, with the percentages subsequently falling from 22% to 12% and from 20% to 5%, respectively.

The percentage of accurate conceptions concerning the heat in an isobaric process increased from 11% to 26%, but a prevalent misconception involving neglect of the impact of work on internal energy increased from 41% to 52% during the intervention. The percentage of uncategorized answers (blank or irrelevant) fell from 22% to 11% during the intervention.

With respect to the kinetic energy of particles in an isothermal process, students' accurate conceptions increased from 51% to 77%. A typical misconception of paralleling the kinetic energy of particles with the wrong quantities, such as pressure or volume, declined from 26% to 15% during the intervention.

The heat in an isothermal process was shown to be a problematic theme because, in the course of our intervention, the proportion of accurate conceptions remained practically unchanged, falling from 29% to 28%. Misconceptions stating that heat equaled zero due to the apparent absence of temperature difference or a zero temperature change increased from 15% to 20% and from 28% to 29%, respectively. Uncategorized responses declined from 17% to 15%. Thus, in this specific task the intervention offered no significant help in overcoming misconceptions.

With respect to the task addressing the heat in an isochoric process, the interpretation of accurate conceptions is slightly ambiguous because of the criteria: it is unclear whether the work equaling zero in an isochoric process should be mentioned explicitly or not. If this is not required[3], the percentage of

[3] This interpretation is in agreement with Meltzer's original article (Meltzer, 2004).

accurate conceptions concerning energy transfer changed from 58% to 74% during the intervention, inaccurate energy conceptions decreased from 17% to 9%, and uncategorized answers from 25% to 11%. However, if it is required that work should be explicitly mentioned as equaling zero in an isochoric process, the percentage of accurate conceptions increased from 12% to 18%, and the percentage of conceptions being otherwise accurate but not stating the work equaling zero changed from 45% to 54%. In consequence, we conclude that this task helped in overcoming some misconceptions and it also increased the percentages of accurate conceptions. However, due to the ambiguity of the criteria, we cannot evaluate the exact percentages of students with accurate conceptions of the first law of thermodynamics applied in an isochoric process.

When students were asked to define a sign of the work done on the gas during a cyclic process, the percentages of accurate conceptions increased from 28% to 51% during the intervention. A prevalent misconception in which work was claimed to equal zero due to the same initial and final states remained almost constant, with a small change from 28% to 29%. A large increase in the percentage of accurate conceptions can be explained as the result of a decrease in the uncategorized answers category, from 26% to 8%

With respect to the students' accurate conceptions, the final task addressing the heat in a cyclic process underwent large increase, from 15% to 40%. As with the previous task, a misconception concerning the same initial and final states causing heat to equal zero was not reduced: rather, the rate increased from 32% to 40% during the intervention. The proportion of uncategorized answers declined from 35% to 9% during the intervention.

### 5.3.3 Post-testing

In order to test the permanence of the intervention, we designed and utilized a new set of tasks in the course exam, which was held two weeks after the actual intervention. In practice, we reversed the direction of the original cyclic process used in the course of the intervention and addressed the same themes so that every question in the original test (Meltzer, 2004) had a counterpart in the course exam. Thus, the same categorization for conceptions was utilized in both the intervention and the course exam. A scatterplot with a regression line in Figure 5.1 presents the percentages of the students' categorized responses in the course exam against the final phase of the intervention.

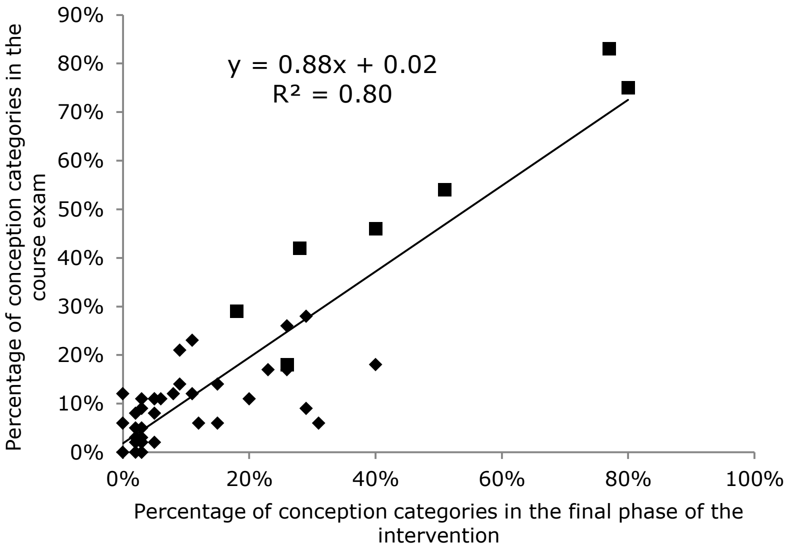


***Figure 5.1.*** *Students' categorized responses in the course exam set against the final phase of the intervention, N=65. The squares refer to the students' accurate conceptions, while the diamonds refer to the misconceptions observed in students' answers.*

It can be seen that the percentages of conceptions remained relatively stable between the intervention and the course exam. This is regarded as evidence that the impact of the intervention was not merely a momentary artifact of the intervention but that it could be seen to prevail beyond the actual intervention – although it must be admitted that a period of only two weeks is a rather modest interval of time. This finding is supported by the observation that the slope of the regression line and R-squared values are close to 1. With respect to the statistical significance of the change evaluated with the aid of McNemar's test, no significant difference was observed between the final phase of the intervention and the course exam ($0.06 < p < 0.65$).

This suggests that the impact of self-study for the course exam was only modest.

# 6 Discussion

In the course of this dissertation a research project has been present that has attempted to improve students' conceptual understanding in thermal physics lecture-based courses without requiring any special resources or training. This principal research aim was pursued with the aid of three sub-aims that targeted university students' conceptions concerning essential thermal physics content in different phases of their thermal physics studies. This section of the study is devoted to a discussion of our research aims in light of previous research in the field, the evaluation of legitimation, trustworthiness, and the validity of the study, while this dissertation is concluded with a brief overview of the perceived relevance of the study, its future prospects, and its implications.

## 6.1 ACHIEVING THE RESEARCH AIMS

Research aim *i*, which was concerned with addressing students' conceptions and reasoning vis-à-vis thermal physics prior to instruction was addressed in articles I and II and also partly in article V. As seen in section 5.1, prior to instruction students possessed numerous misconceptions that affected their understanding of natural phenomena. With respect to the misconceptions concerning individual concepts, our findings agree closely with previous findings. The essential concepts of thermal physics are often paralleled or confused, which is a finding that has been reported previously (Barbera & Wieman, 2009; Beall, 1994; Kautz et al., 2005a; Kesidou & Duit, 1993; Thomaz et al., 1995). It is, however, interesting to notice that a well-reported misconception about paralleling temperature and heat was observed regularly when the students were asked about temperature. On the other hand, references to temperature were relatively uncommon in students' descriptions concerning heat. Students' tendency to rely on microscopic models that were often erroneous is also a familiar finding reported in previous research (Kautz et al., 2005a; Kautz et al., 2005b; Loverude et al., 2002; Thomaz et al., 1995).

Misconceptions concerning students' interpretations of the physical phenomena of thermal physics were also familiar from previous research: the relevance of the first law of thermodynamics was poorly understood, but students often relied on other inoperative explanation models, e.g., the ideal gas law, or ignored a number of important aspects such as the impact of work on internal energy (Barbera & Wieman, 2009; Kautz et al., 2005a; Loverude et al., 2002; Meltzer, 2004; Rozier & Viennot, 1991). It was also observed that students' conceptions can be context-dependent in the sense that they use various explanations that conflict with each other when the context is modified.

With respect to students' reasoning, they tended to concentrate on the surface features of phenomenon rather than finding out what is crucial for a proper understanding of the situation (Chi, Glaser, & Rees, 1928; Hardiman, Dufresne, & Mestre, 1989; Leonard, Dufresne, & Mestre, 1996; Loverude et al., 2002). It was also observed that students' knowledge structures included inconsistencies that they seemed to be unaware of, such as using two conflicting explanations in parallel (Redish, Saul, & Steinberg, 1998). Related to these is an absence of meta-conceptual awareness in students' explanations: they tend to rely on one type of explanation without evaluating its functionality critically (Vosniadou, 1994; Vosniadou & Ioannides, 1998). This is an essential part of scientific thinking that is also mentioned in the Finnish National Curriculum in physics, so expecting this kind of thinking from the students should be a reasonable assumption (NBE, 2003).

Research aim *ii*, which addresses students' conceptions in thermal physics after conventional lecture-based teaching, was dealt with in article III and in some parts of articles IV and V. It was shown that the conventional lecturing and calculation exercises left students with a number of misconceptions. Misconceptions related to the concepts of heat and work are familiar from earlier research, as are the problems concerned with dependencies between quantities, especially with connecting microscopic and macroscopic level explanations (Goldring & Ogborn, 1994; Loverude et al., 2002; Meltzer, 2004; Rozier & Viennot, 1991). Confusion over thermal processes and their properties is also a finding observed previously (Loverude et al., 2002). The finding concerning students' references to the potential energy of ideal gas particles has not been reported previously. This seems to be related to a larger group of problems concerning the meaning of energy in thermal physics content: students are left with various misconceptions concerning thermal/internal energy after exposure to conventional lecture-based teaching.

One finding deserving an extra glance, even if it is not a misconception per se, is a common inability to use *pV* diagrams as a problem-solving tool, even though they have been emphasized during earlier teaching. When the same diagnostic test was used as a basis for interviews, more than third of the students spontaneously used *pV* diagrams (Meltzer, 2004), but in our questionnaire-based study this proportion proved to be only a few percent of the cohort. This may indicate that a majority of students have used the diagrams in a mechanical manner rather than grasping their value as a problem-solving tool.

The final research aim *iii* was addressed in articles IV and V related to the conceptions held by students during and after the HPIL teaching intervention. The intervention proved to be effective in increasing the percentages of accurate conceptions. However, numerous prevalent misconceptions were also observed subsequent to the intervention, which suggests that some of the misconceptions were reluctant to change. With respect to the misconceptions per se, these agreed well with those reported previously (Meltzer, 2004; Loverude et al., 2002; Goldring & Ogborn, 1994; Rozier & Viennot, 1991), but with different percentages. Similar results were obtained in the post-testing phase, which indicates that the impact of the intervention was not simply momentary but also more enduring. In comparisons with previous studies using the same diagnostic test (article III, and Meltzer (2004)), we observed that the percentages of accurate explanations produced at the end of our intervention and in the course exam were typically 15-20 percentage points greater than in the studies mentioned here[4]. Most common misconceptions in our study were typically 10-30 percentage points smaller than found in previous studies, albeit with some exceptions. These figures reinforce the suggestion that the intervention may be able to produce a better learning outcome than conventional teaching alone.

With respect to students' explanations, a substantial increase was observed in the percentages of accurate conceptions. Similarly, a substantial decrease was observed in the percentages of uncategorized responses. Various misconceptions were also reduced significantly. These misconceptions seem to have one feature in common: they may be overcome by applying only one principle of physics. For example, it can be seen that paralleling the kinetic energy of particles with pressure or volume is inaccurate if the student is reminded about the connection between temperature and the average kinetic energy of particles. It must be emphasized, however, that some misconceptions were not reduced as substantially, if at all, during the intervention. What seems to be common in their case is that overcoming them requires the application of more than a single principle. For example, in order to overcome the misconception that heat should equal zero under isothermal conditions, students would need to consider the following ideas concurrently: work done on the gas differs from zero, internal energy remains constant in an isothermal process, and internal energy can be changed via heat

[4] Some approximations have been made with respect to the percentages of correct explanations in Meltzer's (2004) article because they have not been reported by Meltzer for every task. These approximations are likely to positive in nature with regard to the cohort in Meltzer's study.

and work. There seems to be some reluctance to change this kind of misconception with the aid of our intervention. It would appear that the intervention was unable to provide the necessary holistic and comprehensive view required to succeed in the test designed for the whole cohort, an evident deficiency in the intervention.

The principal aim of this research project concerned with improving introductory-level students' conceptual understanding of essential thermal physics content was approached via the sub-aims discussed above. Based on these, we claim that we have been able to achieve the principal aim of the research. By concentrating on students' explanations and the conceptions underlying them provided us with generalizable, yet relatively detailed, data about students' conceptual understanding at different stages in their thermal physics studies. A comparison of the results related to sub-aims *i* and *ii* to those concerning sub-aim *iii* reveals that our intervention assisted students in achieving better learning outcomes than they would have been able to achieve solely from conventional lecture-based teaching. In consequence, we conclude that our intervention, which supplements the conventional lecture-based teaching, can be shown to improve university students' learning when the results are evaluated with the aid of conceptual questionnaires.

## 6.2 LEGITIMATION, TRUSTWORTHINESS, AND VALIDITY

When evaluating mixed methods research, the discussion should focus on both the qualitative and the quantitative elements. In addition, issues emerging from the use of mixed methods need to be evaluated (Creswell, 2009; Creswell & Plano Clark, 2011; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Johnson, 2006; Teddlie & Tashakkori, 2009). Thus, the familiar concepts of trustworthiness and validity can be supplemented with a concept addressing the use of mixed methods per se, namely legitimation (Onwuegbuzie & Johnson, 2006; Johnson &

Christensen, 2008) or inference quality (Teddlie & Tashakkori, 2003). In the present section, therefore, we will present some of the ways in which these are taken into account in this study.

### 6.2.1 Legitimation

The term legitimation has been used in this dissertation in the context of evaluating the use of mixed methods, (Onwuegbuzie & Johnson, 2006). The criteria under inspection follow the ideas put forward by Onwuegbuzie and Johnson (2006) but supplemented by further sources (Johnson & Christensen, 2008; Teddlie & Tashakkori, 2003; Teddlie & Tashakkori, 2009). In this part of our evaluation we will concentrate on the following criteria: sample integration, inside-outside legitimation, weakness minimization, sequential legitimation, conversion legitimation, paradigmatic mixing, and commensurability.

Sample integration refers to the problems faced if qualitative and quantitative samples do not represent the same cohort adequately: combining findings or conclusions from qualitative and quantitative data may reveal or involve problems. In the present study, purely qualitative data is not used to produce generalizations but the data is used to provide answers to a variety of research questions or to illustrate results that are more quantitative in nature. In consequence, we would suggest that sample integration is not an issue concerning the legitimation of the study.

Inside-outside legitimation is related to the accuracy of the presentation of both insider's and outsider's views. These legitimation types are paralleled by member-checking and peer-debriefing, which are discussed in greater detail in section 6.2.2. We admit that, due to the nature of the research, inside-legitimation is mostly ignored in the course of this research. However, all of the articles have undergone peer-reviewing, which in turn enhances outsider legitimation.

Weakness minimization is an essential legitimation type in mixed methods research. It relates to compensating the weaknesses of one approach with the strengths of another. In this study, the relative absence of details in the questionnaires was compensated for by means of interviews and audio recordings. Conversely, questionnaires provided forms of generalization that could not be achieved solely by qualitative methods.

Sequential legitimation refers to the impact of the order, or sequence, of the qualitative and quantitative phases, and is concerned with the vital question of whether changing the order would affect the results. As far as our research is concerned, qualitative and quantitative elements had clear-defined roles that emerged in a certain order. This order emerged from the research design and strategy, which in turn means that changing the order would not simply change results of the research but also its aims and research design. Hence, we would suggest that, in order to achieve our research aims, following the present sequence was an appropriate decision.

Conversion legitimation is an important legitimation type in this study. It refers to the quality of quantifying qualitative data, or the reverse. A large part of the results is based on the quantification of students' responses within the categories describing their conceptions. This legitimation type is evaluated in various ways. Firstly, the fact that students' conceptions and their percentages agree well with previous research indicates that the quantification and categorization have been legitimate. Secondly, we utilized researcher triangulation in some parts of the study in order to ensure the quality of the quantification process. Thirdly, we acknowledged the possibility of ambiguity in the responses by using categorization systems that enabled students' responses to be placed in two or more categories. The categorizations have also been reviewed by external evaluators.

The choice of legitimation type involved in paradigmatic mixing in this study has been decided by relying on pragmatism, which is introduced in section 3.1. In the use that we make of it, this means that assumptions concerning epistemological, ontological, and methodological issues are subordinate to the research aims, which is typical in mixed methods research (Onwuegbuzie & Leech, 2005).

Commensurability refers to switching repeatedly from a qualitative lens to a quantitative lens, and vice versa. This requires that a researcher should be competent in both qualitative and quantitative research. Using both types of research, a mixed researcher should be able to see beyond what a mono-method researcher sees. This legitimation type is not addressed consciously by the researcher, but occurs spontaneously, depending on the stage in the research and the nature of the data. We claim that using mixed methods in a proper manner has provided a broader view of the topic than either method alone could have achieved.

### 6.2.2 Trustworthiness

With respect to the qualitative components of our study, we have based the evaluation of trustworthiness on the following criteria: triangulation, dependability audit, confirmability audit, member checks, peer debriefing, negative case analysis, referential adequacy, and thick description (Creswell, 2009; Guba & Lincoln, 1989; Teddlie & Tashakkori, 2009).

Triangulation in this study was used in two ways. Data triangulation was used to supplement the questionnaire data produced using interviews and audio recordings. Researcher triangulation took place in the context of articles I and II, where double-checking for the data was used. In the case of all of articles, the findings were discussed within the research group, a procedure that can also be regarded as a form of research triangulation.

Dependability audit refers to documenting a research process so that the methodological and other choices are trackable and can be reasoned appropriately. The dependability audit is conducted with the aid of a detailed description concerning the research process. Confirmability audit means that the results and interpretations of the study are examined by external evaluators. This requirement has been fulfilled in the form of the peer-reviewing process that every article I-V has undergone or is about to undergo.

Member-checking refers to asking participants in the study to check on the accuracy of the inferences drawn by a particular researcher. This criterion could not be fulfilled in the course of the present research project. The principal reason for this omission was that the participants, namely students, did not possess an adequate knowledge of the misconceptions that would have enabled them to evaluate the accuracy of findings.
Peer debriefing process involves discussions with "disinterested" peers in order to clarify interpretations and to locate possible biases. Aspects of this study have been presented at various national and international conferences and at graduate school meetings where researchers from other fields have offered valuable critical comments.
Negative case analysis is related to how cases not fitting into the categorization used are discussed and taken into account. In addition to their existence and characteristics being recognized, confidence in the appropriate categorization should be sustained so that no important information is lost as a result of negative cases. In the present study this has been achieved by describing the data analysis processes in detail, and also by discussing cases that do not support the main findings.
Referential adequacy means that part of the data should be put aside during analysis, and after the main analysis has been completed, this data should be used in testing the validity of the analysis. This technique was not used, however, because the samples were only moderate in size; in addition, a somewhat practical approach was used in the data analysis (Lincoln & Guba, 1985). We would also suggest that this technique might involve the risk of missing interesting findings when data-driven analysis is also utilized.
Thick description relates to transferability. A description of the study needs to include sufficient information about the context, time, and participants, so that readers can assess whether the study has enough similarities to their own so that they could transfer some of its elements for their own use. This criterion is fulfilled with detailed descriptions concerning the courses, cohorts, and necessary background information.

### 6.2.3 Validity

A quantitative approach was used with students' open responses, which were quantified by following the basics of content analysis in all but article IV, which focused evaluating students' answers solely in a quantitative manner. In addition, the significance of the findings was evaluated statistically in article V with the aid of McNemar's test. Evaluating validity was based on the following four criteria: statistical conclusion validity, internal validity, construct validity, and external validity (Creswell, 2009; Trochim, 2006; Teddlie & Tashakkori, 2009). Assessing the reliability of the study is in-built in these criteria and so it is not discussed separately. The evaluation is conducted on a discretionary basis, so that self-explanatory sub-criteria, such as threats posed by the maturation and attrition of the students, are not discussed.

Statistical conclusions are drawn in all of articles I-V, but the conclusions have a greater weight in articles IV and V because in those we have evaluated changes as well as static conceptions. The relatively small sample sizes mean that the statistical interpretations have to be treated critically. With respect to the reliability of the measurements, we have mainly utilized diagnostic tasks published in peer-reviewed journals or those used in national-level examinations, which is an indication that their reliability has evaluated thoroughly (FMEB, 2012; Loverude et al., 2002; Meltzer, 2004).

According to Teddlie and Tashakkori (2009), internal validity means that a causal relationship for the treatment and the results has to be ensured. The possible impact of selection bias can be ignored because samples are examined as whole entities. There is nevertheless the possibility of a bias caused by repeated testing, which is a threat that deserves more detailed attention, since the same themes were addressed several times in the course of the intervention and in the post-test. In the intervention this was not a problem because the intervention required responses to the same questions several times with no intervals. A procedure of this kind may cause fatigue, but it is unlikely to result in bias. With respect to the post-testing, which addressed the same themes, we would suggest that the tests were different to such an extent that students would have been unable to succeed in the post-test without really understanding the content. This claim is reinforced by the fact that use of the post-test has also been approved by three external evaluators.

Construct validity refers to the accuracy of measurements and conclusions (Teddlie & Tashakkori, 2009). A potential bias that might have been caused by a possible interaction with testing and intervention is, however, no cause for concern since the two criteria are intended to be connected: testing is part of the intervention as a whole. One aspect that needs to be taken into account, however, is the possibility of outcomes other than the desired one. This can be dealt with by evaluating and discussing changes in the misconception categories. Some social threats may affect the construct validity. Hypothesis guessing is not an issue in this study, however, as the aim of our research to improve a learning outcome is presumably self-evident to students and would not affect their content knowledge. That some students may feel a degree of apprehension because of the evaluation may, however, pose a real threat. This was addressed by emphasizing that none of the tests, except a post-test in the course exam, would affect grading. The last social threat, that of experimenter expectancies, should not have had much of an impact because the intervention was designed so that the personality of an experimenter would play no role in the intervention.

External validity is related to generalization of the results. It refers to the extent to which the students' inferences could be applied in other contexts (Teddlie & Tashakkori, 2009). The cohort and its properties themselves may pose a threat to the external validity. In this study, we have described our samples in great detail in order to place some responsibility on the reader themselves to undertake evaluation of this threat. A threat posed by biased sampling is not an issue in the context of this study since the cohorts were examined together. With respects to a threat emerging from the context, we consider our general context consisting of lecture-based teaching and homework sessions to be rather typical, at least as far as Finland is concerned. In addition, the same textbooks are used widely in many other Finnish institutions, which means that there are no great differences in the content of the courses.

### 6.3 CONCLUSIONS AND OUTLOOK

Arguably, this study has both theoretical and practical relevance. Its theoretical relevance is related to the kind of conceptions and reasoning practiced by students that we have evaluated in the different phases of their university studies. Earlier research was extended and deepened with new findings concerning students' conceptions, explanations, reasoning, and discussions concerning the content of thermal physics. The practical relevance can be seen in the innovatory intervention, which appeared to help students to achieve a better conceptual understanding. These theoretical and practical elements may provide both educational researchers and teachers with valuable information. Researchers can also utilize our findings by extending or deepening them and also by designing new types of teaching interventions. For their part, teachers can implement our intervention in their own courses or use it as a basis for alternative ways of enhancing the effectiveness of their lecture-based teaching. Regardless of the fact that we have concentrated on university students, we also think that some of our findings may even be applicable at lower school levels. For example, we think that peer discussions could also be used systematically at secondary level because of their undisputable value in enhancing learning.

Regarding the outlook for future research in this field, we think that research concerning students' misconceptions is already relatively extensive. Nevertheless, there is still work that could be done in terms of the evaluation of students' reasoning and the thinking underlying their conceptions. The interview data introduced in article II demonstrated that students' reasoning differs greatly from experts' reasoning, a topic that should be studied in greater depth in the context of thermal physics. Moreover, the role of peer discussions in learning would deserve a more extensive and detailed study where a greater emphasis might be placed on the characteristics of the discussants and their initial conceptions. In this way the benefits of discussions could be better understood, which would in turn help in the designing of new materials and interventions that would ultimately result in better learning outcomes.

The results related to students' conceptions and reasoning in the course of their thermal physics studies revealed various implications concerning curricula, materials, and the teaching itself. With respect to the findings concerning students' conceptions prior to instruction, we would like to open up a discussion about the content of thermal physics in upper secondary level education. In particular, we would like to address the emphases that would be significant for in teaching, since the ideal gas law and the microscopic models appear to dominate in students' thinking at the expense of the first law of thermodynamics, one of the strongest principles in physics as a whole. Unquestionably, these are all important topics in the field of teaching, but we suggest a re-assessment of the emphasis and the sequencing of the content. Typically, the first law of thermodynamics is introduced in the closing chapters of upper secondary textbooks, which means that it may not be receiving the emphasis that it deserves (NBE, 2003).

In addition, we recommend the implementation of this material (Meltzer, 2004) in the course of upper secondary studies in order to improve students' conceptual learning. Naturally, its applicability will depend on the national curriculum. In the Finnish educational system, it may also be appropriate material for testing and teaching the concepts and principles of thermal physics at the upper secondary level (NBE, 2003).

With respect to the results concerning students' conceptions in general, we would like to see more calls upon these in practice. There are plenty of things that researchers already know about learning, teaching, and students' conceptions, but we would suggest that these could be utilized in teaching and in designing new materials more effectively. There are some examples of the utilization of physics education research findings in textbooks (Knight, 2008) and we would strongly encourage other textbook authors to familiarize themselves with these findings. These findings should not be concealed within the body of the scientific community but they should also spread to the large number of teachers and lecturers at all levels of school education. We are now considering further ways of developing teaching that could be applied both through this type of intervention and also in the course of conventional teaching at upper secondary level. In its current form, our intervention offers a way to enhance lecture-based instruction in terms of an improved learning outcome. Our findings, however, suggest that there are considerable problems to be overcome with regard to more effective teaching of phenomena that require the utilization of several physics principles concurrently, especially in contrast to the problems that can be overcome when only a single principle is involved. Similar findings concerning this kind of *local thinking*, rather than evaluating phenomena comprehensively, have been observed in relation to direct current circuits, and hence it can be said that this is not solely a problem of thermal physics (Cohen, Eylon, & Ganiel, 1982; McDermott & Shaffer, 1992). Rather than directing students to rely on individual principles, we should emphasize holistic reasoning and thinking in teaching, since this is where the strength and explanatory power of physics originates from.

In consequence, we would urge lecturers and teachers to challenge students' explanations and reasoning by offering them tasks related to phenomena that cannot be explained and understood properly if their concentration is solely on individual principles. Some of the materials used in the course of this research are functional examples of these types of tasks. However, as our results indicate, making a positive impact on students' holistic reasoning is unlikely to be achieved simply by introducing these types of tasks to students. Such tasks may offer a context for students to construct a coherent holistic understanding, but they may well also need some type of guidance in evaluating situations comprehensively and in applying various principles concurrently.

We are also considering about ways in which extensive research about misconceptions might be better utilized in teaching. It would appear that simply introducing misconceptions per se to students is not helpful in itself, but students should be trusted to reflect on their own ideas regarding misconceptions. This is strongly related to meta-conceptual awareness, a concept that means that a learner should evaluate his or her own conceptions critically to develop a better personal conceptual understanding (Asikainen & Hirvonen, 2009; Vosniadou & Ioannides, 1998).

In addition, we would suggest that this type of intervention could be widened to cover whole courses. For example, a typical introductory thermal physics course could include this type of intervention to follow on from instruction concerning thermal processes and the first law, the second law, and heat engines. We would also suggest that teachers and lecturers might explicitly emphasize the most important parts of the content taught. Learning aims should be made self-evident for students. Similar interventions and materials may help in this because this type of material should be used to construct the most essential content.

In closing, we would again encourage researchers and teachers to design and test similar interventions in other areas of physics. The problems involved in conventional lecture-based teaching are widely acknowledged, but making lectures more efficient is not a trivial task. This type of intervention designed to supplement conventional teaching with activating elements may indeed prove to be a way to accomplish this.

# References


Alexopoulou, E., & Driver, R. (1996). Small-group discussions in physics - Peer interaction modes in pairs and fours. *Journal of Research in Science Teaching, 33*(10), 1099-1114.

Asikainen, M. A., & Hirvonen, P. E. (2009). A study of pre- and inservice physics teachers' understanding of photoelectric phenomenon as part of the development of a research-based quantum physics course. *American Journal of Physics, 77*(7), 658-666.

Atkins, P., & De Paula, J. (2006). *Atkins' physical chemistry, 8th edition*. Oxford: Oxford University Press.

Barbera, J., & Wieman, C. E. (2009). Effect of a dynamic learning tutorial on undergraduate students' understanding of heat and the first law of thermodynamics. *The Chemical Educator, 14*(2), 45-48.

Baser, M. (2006). Fostering conceptual change by cognitive conflict based instruction on students' understanding of heat and temperature concepts. *Eurasia Journal of Mathematics, Science and Technology Education, 2*(2), 96-114.

Beall, H. (1994). Probing student misconceptions in thermodynamics with in-class writing. *Journal of Chemical Education, 71*(12), 1056-1057.

Bloor, M., & Wood, F. (2006). Audio-recording. Keywords in qualitative methods. London: Sage Publications Ltd.

Blundell, S. J., & Blundell, K. J. (2006). *Concepts in Thermal Physics.* New York: Oxford University Press.

Bryman, A. (2012). *Social research methods.* Oxford: Oxford University Press.

Bucy, B., Thompson, J., & Mountcastle, D. (2005). What is entropy? Advanced undergraduate performance comparing ideal gas processes. *Physics Education Research Conference*, (pp. 81-84). Salt Lake City.

Burnard, P. (1996). Teaching the analysis of textual data: An experiential approach. *Nurse Education Today, 16*, 278-281.

Chabay, R., & Sherwood, B. (2011). *Matter&interactions, 3rd edition*. New York: John Wiley&Sons, Inc.

Chaiklin, S. (2003). The zone of proximal development in Vygotsky's analysis of learning and instruction. In A. Kozulin, B. Gindis, V. S. Ageyev, & S. M. Miller, *Vygotsky's Educational Theory in Cultural Context* (pp. 39-65). Cambridge: Cambridge University Press.

Chi, M. T. (1996). Constructing self-explanations and scaffolded explanations in tutoring. *Applied Cognitive Psychology, 10*, 33-49.

Chi, M. T., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. J. Sternberg, *Advances in the psychology of human intelligence* (pp. 7-76). Hillsdale: Erlbaum.

Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education, 11*, 554-565.

Cochran, M. (2005). *Student understanding of the second law of thermodynamics and the underlying concepts of heat, temperature, and thermal equilibrium.* Washington: Unpublished dissertation.

Cohen, R., Eylon, B., & Ganiel, U. (1982). Potential difference and current in simple electric circuits: A study of students conceptions. *American Journal of Physics, 51*(5), 407-412.

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L. B. Resnick, *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser* (pp. 453-494). Hillsdale, NJ: Lawrence Erlbaum Associates.

Cooper, J. L., & Robinson, P. (2000). Getting started: Informal small-group strategies in large classes. *New Directions for Teaching and Learning, 2000*(81), 17-24.

Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed methods approaches, third edition.* Thousand Oaks: SAGE Publications, Inc.

Creswell, J. W., & Plano Clark, V. L. (2011). *Designing and conducting mixed methods research.* California: Sage.

Crouch, C. H., & Mazur, E. (2001). Peer instruction: Ten years of experience and results. *American Journal of Physics, 69*(9), 970-977.

Davis, E. A. (2000). Scaffolding students' knowledge integration: Prompts for reflection in KIE. *International Journal of Science Education, 22*(8), 819-837.

Durkalski, V. L., Palesch, Y. Y., Lipsitz, S. R., & Rust, P. F. (2003). Analysis of clustered matched-pair data. *Statistics in Medicine, 22*, 2417-2428.

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing, 62*(1), 107-115.

FMEB (The Finnish Matriculation Examination Board). (19.9.2011). *Physics exam*. Retrieved May 5, 2013, from http://www2.hs.fi/ extrat/kotimaa/yo11syksy/1909/Fysiikka-S11.pdf

Ge, X., & Land, S. M. (2003). Scaffolding students' problem-solving processes in an ill-structured task using question prompts and peer interactions. *Educational Technology Research and Development , 51*(1), 21-38.

Gertner, A. S., & VanLehn, K. (2000). Andes: A coached problem solving. In G. Gauthier, C. Frasson, & V. Kurt (Ed.), *Intelligent Tutoring Systems - 5th International Conference, ITS 2000* (pp. 133-142). Montreal: Springer.

Gillham, B. (2005). *Research interviewing - The range of techniques.* London: Open University Press.

Goldring, H., & Ogborn, J. (1994). Students' difficulties with energy and related concepts. *Physics Education, 29*, 26-32.

Gorard, S., & Taylor, C. (2004). *Combining methods in educational and social research.* Maidenhead: Open University Press.

Greene, J. C. (2008). Is mixed methods social inquiry a distinctive methodology. *Journal of Mixed Methods Research*, 7-22.

Greening, T. (1998). Scaffolding for success in problem-based learning. *Medical Education Online, 3*, 1-15.

Guba, E. G., & Lincoln, Y. S. (1989). *Fourth generation evaluation.* Newbury Park: Sage.

Gunstone, R., McKittrick, B., & Mulhall, P. (1999). Structured cognitive discussions in senior high school physics: Student and teacher perceptions. *Research in Science Education, 29*(4), 527-546.

Hammer, D. (1996). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics, 10*, 1316-1325.

Hansman, C. A. (2001). Context-based adult learning. *New directions for adult and continuing education, 2001*, 43-52.

Hardiman, P. T., Dufresne, R., & Mestre, J. P. (1989). The relation between problem categorization and problem solving among novices and experts. *Memory&Cognition, 17*(5), 627-638.

Howe, K. R. (1988). Against the quantitative-qualitative incompatibility thesis or dogmas die hard. *Educational Researcher*, 10-16.

Hsieh, H.-F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277-1288.

Johnson, B., & Christensen, L. (2008). *Educational research: Quantitative, qualitative, and mixed approaches, 3rd edition.* California: Sage Publications, Inc.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, 14-26.

Jones, M. G., & Carter, G. (1998). Small groups and shared constructions. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak, *Teaching science for understanding - A human constructivist view* (pp. 261-279). New York: Academic Press.

Kautz, C. H., Heron, P. R., Loverude, M. E., & McDermott, L. C. (2005a). Student understanding of the ideal gas law, Part I: A macroscopic perspective. *American Journal of Physics, 73*(11), 1055-1063.

Kautz, C. H., Heron, P. R., Shaffer, P. S., & McDermott, L. C. (2005b). Student understanding of the ideal gas law, Part II: A microscopic perspective. *American Journal of Physics, 73*(11), 1064-1071.

Kesidou, S., & Duit, R. (1993). Students' conceptions of the second law of thermodynamics – An interpretive study. *Journal of Research in Science Teaching, 30*(1), 85-106.

Knight, R. D. (2008). *Physics for scientists and engineers – A strategic approach (Second edition).* San Francisco: Pearson.

Knight, R. D. (2013) *Mastering Physics*. Retrieved January 10, 2013, from Mastering Physics: http://www.masteringphysics.com/

Koedinger, K. R., & Corbett, A. (2005). Cognitive tutors: Technology bringing learning science to the classroom. In K. R. Sawyer, *The Cambridge Handbook of the Learning Sciences* (pp. 61-77). Cambridge: Cambridge University Press.

Krippendorff, K. (2004). *Content analysis: An introduction to itse methodology (2nd edition).* CA: Sage Publications, Inc.

Kvale, S. (1996). *InterViews - An introduction to qualitative research interviewing.* Thousand Oaks: Sage Publications.

Lasry, N., Mazur, E., & Watkins, J. (2008). Peer instruction: From Harvard to the two-year college. *American Journal of Physics, 76*(11), 1066-1069.

Leonard, W. J., Dufresne, R. J., & Mestre, J. P. (1996). Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems. *American Journal of Physics, 64*(12), 1495-1503.

Lincoln, Y., & Guba, E. G. (1985). *Naturalistic Inquiry.* Newbury Park: Sage.

Lindstrøm, C., & Sharma, M. D. (2009). Link maps and map meetings: Scaffolding student learning. *Physical Review Special Topics: Physics Education Research, 5*(1), 010102.

Loverude, M. E., Kautz, C. H., & Heron, P. R. (2002). Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas. *American Journal of Physics, 70*(2), 137-148.

Maxcy, S. J. (2003). Pragmatic threads in mixed methods research in the social sciences: The search for multiple modes of inquiry and the end of the philosophy of formalism. In A.

Tashakkori, & C. Teddlie, *Handbook of Mixed Methods in Social & Behavioral Research* (pp. 51-90). California: Sage.
Mayring, P. (2000). Qualitative content analysis. *Forum: Qualitative Social Research, 1*(2). Retrieved from http://www.qualitative-research.net/index.php/fqs/article/view/1089
McDermott, L. C., & Shaffer, P. S. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding. *American Journal of Physics, 60*(11), 994-1003.
McDermott, L. C., & Shaffer, P. S. (2010). *Tutorials in Introductory Physics.* Boston: Pearson.
Meltzer, D. (2004). Investigation of students' reasoning regarding heat, work, and the first law of thermodynamics in an introductory calculus-based general physics course. *American Journal of Physics, 72*(11), 1432-1446.
Munn, P., & Drever, E. (1995). *Using questionnaires in a small-scale research: A teacher's guide.* Edinburgh: Scottish Council for Research in Education.
NBE (The National Board of Education). *National core curriculum for upper secondary schools 2003*. Retrieved 11 30, 2012, from http://www.oph.fi/download/47678_core_curricula_upper_secondary_education.pdf
Onwuegbuzie, A. J., & Johnson, R. B. (2006). The validity issue in mixed research. *Research in the Schools, 13*(1), 48-63.
Onwuegbuzie, A. J., & Leech, N. L. (2005). On becoming a pragmatic researcher: The importance of combining quantitative and qualitative research methodologies. *International Journal of Social Research Methodology*, 375-387.
Palinscar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition&Instruction, 1*(2), 117-175.
Patton, M. Q. (2002). *Qualitative Research & Evaluation Methods (3rd edition).* Thousand Islands: Sage.
Puntambekar, S., & Hübscher, R. (2005). Tools for scaffolding students in a complex learning environment: What have we

gained and what have we missed? *Educational Psychologist, 40*(1), 1-12.

Puntambekar, S., & Kolodner, J. (2005). Toward implementing distributed scaffolding: Helping students learn science from design. *Journal of Research in Science Teaching, 42*(2), 185-217.

Rao, S. P., & DiCarlo, S. E. (2000). Peer instructions improves performance on quizzes. *Advances in Physiology Education, 24*(1), 51-55.

Redish, E. F., Saul, J. M., & Steinberg, R. N. (1998). Student expectations in introductory physics. *American Journal of Physics, 66*(3), 212-224.

Robertson, A. D., & Shaffer, P. S. (2013). University student and K-12 teacher reasoning about the basic tenets of kinetic-molecular theory, Part I: Volume of an ideal gas. *American Journal of Physics, 81*(4), 303-312.

Rozier, S., & Viennot, L. (1991). Students' reasonings in thermodynamics. *International Journal of Science Education, 13*(2), 159-170.

Schroeder, D. V. (2000). *An introduction to thermal physics.* San Francisco: Addison Wesley.

Stake, R. E. (1995). *The art of case study research.* Thousand Oaks: Sage Publications.

Teddlie, C., & Tashakkori, A. (2003). Major issues and controversies in the use of mixed methods in the social and behavioral sciences. In A. Tashakkori, & C. Teddlie, *Handbook of Mixed Methods in Social & Behavioral Research* (pp. 3-50). California: Sage.

Teddlie, C., & Tashakkori, A. (2009). *Foundations of mixed methods research - Integrating quantitative and qualitative approaches in the social and behavioral sciences.* California: SAGE Publications.

Thomas, P. L., & Schwenz, R. W. (1998). College physical chemistry students' conceptions of equilibrium and fundamental thermodynamics. *Journal of Research in Science Teaching, 35*(10), 1151-1160.

Thomaz, M. F., Malaquias, I. M., Valente, M. C., & Antunes, M. J. (1995). An attempt to overcome alternative conceptions related to heat and temperature. *Physics Education, 30*(1), 19-26.

Trochim, W. M. (2006, 10 20). *Research methods knowledge base, 2nd edition.* Retrieved 3 20, 2013, from http://www.socialresearchmethods. net/kb/

Tuomi, J., & Sarajärvi, A. (2002). *Laadullinen tutkimus ja sisällönanalyysi.* Jyväskylä: Tammi.

van Roon, P. H., van Sprang, H. F., & Verdonk, A. H. (1994). 'Work' and 'heat': On a road towards thermodynamics. *International Journal of Science Education, 16*(2), 131-144.

Vanlehn, K., Lynch, C., Schulze, K., Shapiro, J. A., Shelby, R., Taylor, L., . . . Wintersgrill, M. (2005). The andes physics tutoring system: Five years of evaluations. *International Journal of Artificial Intelligence in Education, 15*(3), 147-204.

VanLehn, K., Lynch, C., Schulze, K., Shapiro, J. A., Shelby, R., Taylor, L., . . . Wintersgrill, M. (2005). The Andes Physics Tutoring System: Lessons Learned. *Proceedings of the 12th International Conference on Artificial Intelligence in Education. 15*, pp. 638-645. Amsterdam: IOS press.

Warren, J. W. (1972). The teaching of the concept of heat. *Physics Education, 7*(1), 41-44.

Weber, R. P. (1990). *Basic Content Analysis.* Newburry Park: Sage.

Weiss, R. S. (1994). *Learning From Strangers: The Art and Method of Qualitative Interview Studies.* New York: The Free Press.

Wiser, M., & Tamer, A. (2001). "Is heat hot?" Inducing conceptual change by integrating everyday perspectives on thermal phenomena. *Learning and Instruction, 11*, 331-355.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry, 17*, 89-100.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45-69.

Vosniadou, S. (2002). On the nature of naïve physics. In *Reconsidering Conceptual Change: Issues in Theory and Practice* (pp. 61-76). Netherlands: Kluwer.

Vosniadou, S., & Ioannides, C. (1998). From conceptual development to science education: a psychological point of view. *International Journal of Science Education, 20*(10), 1213-1230.

Vygotsky, L. (1978). Interaction between learning and development. In M. Cole, V. John-Steiner, V. Scribner, & E. Souberman, *Mind and Society - The Development of Higher Psychological Processes* (pp. 79-91). Cambridge: Harvard University Press.

Yeo, S., & Zadnik, M. (2001). Introductory thermal concept evaluation: Assessing students' understanding. *The Physics Teacher, 39*, 496-504.

Young, H. D., & Freedman, R. A. (2004). *University physics with modern physics, 11th edition.* San Francisco: Pearson.

Zemansky, M. W. (1970). The use and misuse of the word "heat" in physics teaching. *The Physics Teacher, 8*, 295-300.

Zhou, Y., Freedman, R., Glass, M., Michael, J. A., Rovick, A. A., & Evens, M. W. (1999). Delivering hints in a dialogue-based intelligent tutoring system. *Proceedings of the Sixteenth National Conference on Artificial Intelligence (AAAI-99)*, (pp. 128-134). Orlando.

**Risto Leinonen**

*Improving the learning of thermal physics at university*

This thesis focuses on improving learning of essential thermal physics content in the context of introductory thermal physics courses at university. Students' conceptions are monitored prior, during, and after conventional teaching. A novel teaching intervention is developed to address the well-known difficulties that students face with thermal physics content. Students' conceptions after the teaching intervention are evaluated. Implications for teaching practices in university and upper school levels are presented.

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