Integrating Cognitive Learning Strategies into Physics Instruction

Developing students' approaches to physics and learning

Vegard Gjerde

Thesis for the degree of Philosophiae Doctor (PhD)
University of Bergen, Norway
2021

UNIVERSITY OF BERGEN

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Date of defense: 24.03.2021

Year: 2021
Title: Integrating Cognitive Learning Strategies into Physics Instruction

Name: Vegard Gjerde
Print: Skipnes Kommunikasjon / University of Bergen

Scientific environment

This PhD dissertation was written at the University of Bergen, Faculty of Mathematics and Natural Sciences, Department of Physics and Technology.

The thesis was funded by the University of Bergen.

Acknowledgements

This dissertation has never felt like work and I have thoroughly enjoyed it. I would like to thank the University of Bergen for giving me this opportunity to pursue my interests.

I have received a lot of support. I would like to thank my main supervisor, Stein Dankert Kolstø, for providing me with the space to go where my interests took me, the support to make it possible, and the interesting discussions that forced me to think harder. I always felt that you believed in me and I feel lucky to have had you as my supervisor. I would like to thank all my co-supervisors, Bodil Holst, Matthias Gregor Stadler, and Åge Diseth, for agreeing to help me become a Ph.D. A special thanks goes to Bodil Holst who believed in my ideas and gave me an arena to test them out. I have benefited greatly from your honest feedback and advice. You have been a mentor. I would like to thank Mildrid Kyte for valuable and interesting discussions during our semi-regular seminars with Stein Dankert, Matthias, and, later, Vegard.

I have been blessed with some great friends during my studies. I would like to thank Arthur Uno Rognmo for the years of (raucous) laughter and for the deep discussions about everything under the sun. I would like to thank Vegard Havre Paulsen for all the adventures, for joining the office, and for all the deep discussions about everything under, over, and beyond the sun. I would like to thank Mathias Grønstad for agreeing to make an online course about learning with me almost six years ago, which set me on this path.

I would like to thank my mom and dad for always supporting me, believing in me, and giving me a great childhood.

Finally, I would like to thank my son, Isak, and my wife and best friend, Elise, for filling my life with purpose, joy, and love.

Bergen, December 2018

Vegard Gjerde

Abstract

Introductory physics courses are obligatory for many disciplines outside of physics. As experienced by many students, they are notoriously difficult, often with high failure rates. Many students, whether they passed or failed a physics course, fail to acquire the required conceptual knowledge and skill to become able to model complex situations with physics principles. In some cases, this can be attributed to a lack of study time; in many cases, it can be attributed to inefficient learning strategies.

The aim of this thesis was to find ways to create self-regulated physics students who use effective learning strategies, achieve a deep understanding of physics principles, and, ultimately, become able to solve conceptually challenging physics problems through the use of physics modeling.

In this research project, we have identified and tried to fill some of the gaps in students' knowledge that hinder them from becoming able to practice physics modeling. Research within cognitive science, educational psychology, and physics education has informed us about the structure of the knowledge students fail to learn. We matched proven, effective learning strategies to each aspect of this cognitive knowledge structure and we developed tools for scaffolding the process.

In the first phase of the first paper, we investigated students' memory for physics principles and basic facts shortly before the exam and experimentally tested the efficacy of retrieval practice of a novel hierarchical principle structure for improving their declarative memory. The results showed that many of the control group students had a severe lack in their memory for basic facts and principles and that seventy minutes of retrieval practice resulted in large gains for the experimental group. In the second phase, we implemented structured retrieval practice in lectures throughout the semester. The multiple regression model indicated that retrieval practice improved students' results on the final exam, especially for the weaker students.

In the second paper, we quasi-experimentally (study 1) and experimentally (study 2) tested the effects of doing retrieval practice before self-explanation on posttest problem-solving and conceptual scores. In sum, results indicated a medium-sized effect of doing retrieval practice on the problem-solving score. The results were inconclusive for the score on conceptual tests. We also investigated the knowledge students should seek to acquire when self-explaining worked examples in physics. The results from the two studies indicated that when explaining the physics model, students should seek to explicate the principles and their conditions of application, how the principle is set up, and how the physics model can lead to the goal of the problem; and when explaining the mathematical procedures, students should seek to explicate what is done in the particular procedural action, the goal of that action, and the conditions for its application.

In the third paper, we built on the results and experiences from the first two papers and tried to integrate three learning strategies and three scaffolding tools into an introductory mechanics course. The three learning strategies were elaborative encoding for acquiring associative links within and between physics principles; retrieval practice for building strong memories of physics principles; and self-explanations for building effective declarative rules for problem-solving. The three tools were: A set of elaborative encoding-questions as a scaffold for elaborative encoding; the Hierarchical Principle Structure for Mechanics, which together with retrieval practice was meant for scaffolding students' construction of a meaningful and hierarchical cognitive knowledge structure; and a problem-solution structure with emphasis on physics modeling for scaffolding self-explanation and for developing knowledge and skills in physics modeling. Using thematic analysis, we found that the two main encoding strategies—elaborative encoding and self-explanation—require substantial work for overcoming the existing barriers to student adoption and achieving effective implementation. We had more success with the integration of retrieval practice, the hierarchical principle structure, and the practice of physics modeling during problem-solving. The paper provided multiple suggestions for how to overcome barriers and better integrate these learning strategies and tools into the structure of physics courses.

Together, these three papers contribute to the physics education research literature with increased knowledge of how we can support students' conceptual learning, from simple cognitive learning processes like elaborative encoding to the complex practice of physics modeling; with new tools for scaffolding students' conceptual learning in introductory physics, especially the Hierarchical Principle Structure for Mechanics and the problem-solution structure; and with insights into barriers to students' adoption of effective learning strategies.

List of Publications

Gjerde, V., Holst, B., & Kolstø, S. D. (2020). Retrieval practice of a hierarchical principle structure in university introductory physics: Making stronger students. Physical Review Physics Education Research, 16(1), 013103. https://doi.org/10.1103/PhysRevPhysEducRes.16.013103

Gjerde, V., Paulsen, V. H., Holst, B., & Kolstø, S. D. (submitted). Problem solving in basic physics: Effective self-explanations based on four elements with support from retrieval practice.

Gjerde, V., Holst, B., & Kolstø, S. D. (in review). Integrating Effective Learning Strategies in Basic Physics Lectures: A Thematic analysis.

Statement of declaration for the thesis

	Paper I	Paper II	Paper III
Research idea	**VG**	**VG**	**VG**, SDK, BH
Data collection	**VG**, BH	**VG**, BH	**VG**, SDK, BH
Data analysis	**VG**	**VG**, SDK, BH, VHP	**VG**
Data Interpretation	**VG**	**VG**, SDK, VHP	**VG**, SDK
Writing of manuscript	**VG**	**VG**	**VG**
Comments on manuscript	BH, SDK	SDK, BH, VHP	BH, SDK
Approved final version	**VG**, SDK, BH	**VG**, SDK, BH, VHP	**VG**, SDK, BH

Note. Authors listed in order of contribution. Bold face means that the person led the process.

VG = Vegard Gjerde; SDK = Stein Dankert Kolstø; BH = Bodil Holst, VHP = Vegard Havre Paulsen

Contents

1. Introduction

> *Learning results from what the student does and thinks, and only from what the student does and thinks. The teacher can advance learning only by influencing what the student does to learn.* Herbert A. Simon (1916-2001)

From the start of my Ph.D., I have had two main goals. The first goal was to come out of these four years with a deep understanding of knowledge and learning. The second goal was to help as many students as possible to become effective, self-regulated learners. Thankfully, there is no foreseeable end to either of these goals, so they will probably and hopefully keep me going for the decades to come. These two goals have ultimately resulted in the hierarchical structure of my Ph.D. depicted in Figure 1. It depicts how the top-down influence from the overarching aim of my Ph.D. and the bottom-up influence from my theoretical interests in learning and knowledge have been bridged through matching known effective learning strategies to the cognitive knowledge structure, with the designed tools filling in the gaps.

The constraints of working with human beings, with their unique personalities, abilities, and motivations, have provoked continual changes in my understanding and implementation of learning strategy interventions. Dealing with these constraints, I have gone from one-off interventions with motivated students to integration of learning strategies into the structure of physics courses; from complex problem-solving strategies to simpler problem-solving strategies and all the way down to basic cognitive learning processes.

My first intervention was with a complex problem-solving process developed during the autumn of 2017 where I tried to do too much with one piece of paper, see three versions of the Problem-Solving Process-sheet in appendix 7.3. This work was never published, but the underlying ideas were further developed into the coding scheme for self-explanations in paper II and the simplified problem-solution structure in paper III. After the unpublished intervention with the Problem-Solving Process, the focus went gradually away from procedural problem-solving skills and more towards foundational declarative learning, see section 2.1 for definitions. My experiences and continued reading of the literature indicated that this would be a more fruitful route, even for improving students' acquisition of procedural skills.

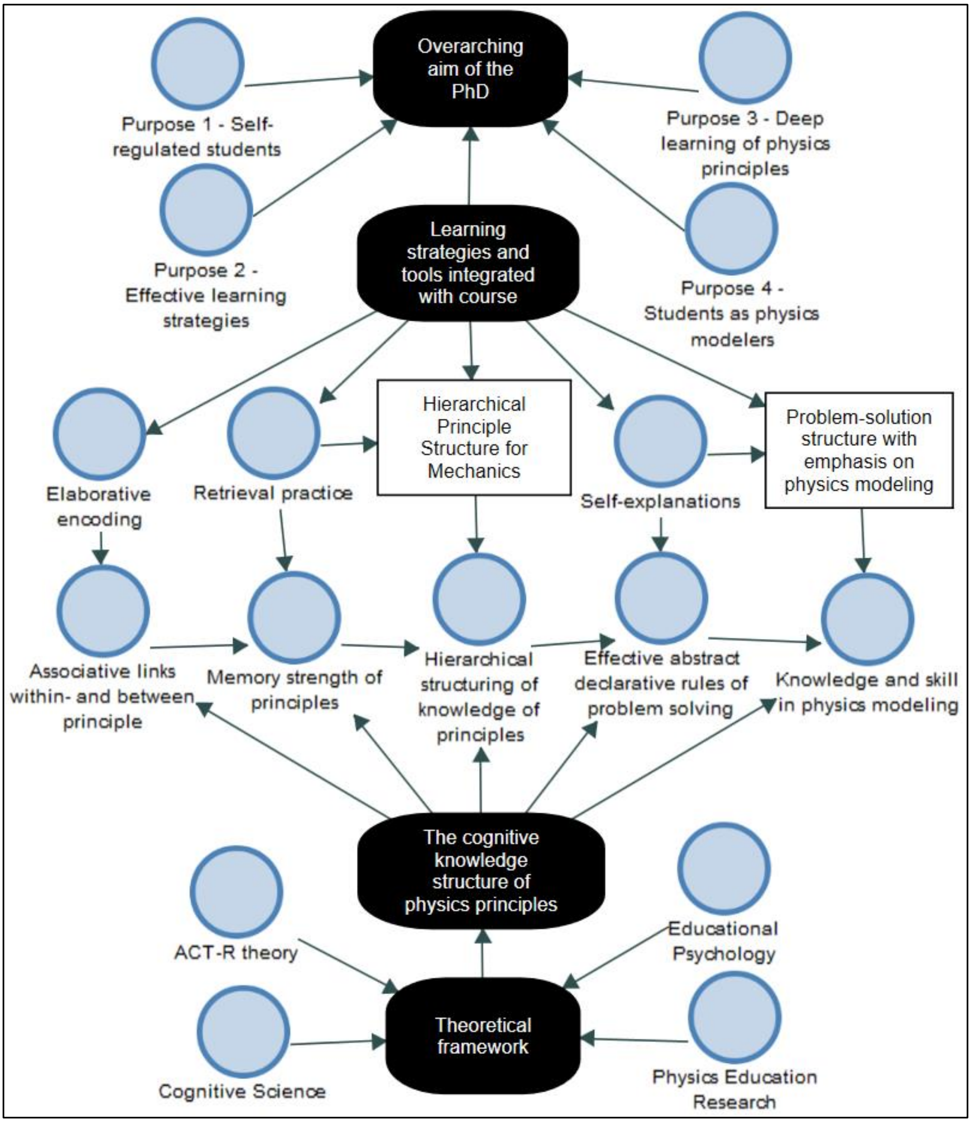


Figure 1 – The hierarchical structure of the Ph.D. The white rectangles are tools I designed. The five aspects of the cognitive knowledge structure are organized in rough order of basic to complex from left to right, each building on the previous, with the corresponding learning strategies and tools matched with these from left to right.

The Hierarchical Principle Structure for Mechanics (HPSM) was developed during the spring of 2018 as a scaffolding tool for physics modeling during problem-solving and for self-explanations of solutions, see appendix 6.4 for the first and last version. Retrieval practice was chosen as a fitting learning strategy for increasing the cognitive availability and accessibility of the physics principles in HPSM. The combination of retrieval practice and HPSM was first introduced in paper I and has played an integral part in all three papers.

In the spring of 2018 and 2019, parallel studies were conducted on retrieval practice of the Hierarchical Principle Structure for Mechanics and on self-explanations of worked examples. In the spring of 2019, we integrated retrieval practice into the lectures of an introductory mechanics course. The experiences from this intervention, the feedback from the students, and continued reading of the literature made it clear that we needed to include an encoding strategy in order to maximize the benefits from retrieval practice and to alleviate some of the students' concerns about lack of understanding. Therefore, we also included elaborative encoding in the retrieval practice sessions of the spring of 2020 as a learning strategy for new and unstudied principles, implemented through the use of a set of elaborative encoding-questions (see section 2.3 for definitions of elaborative encoding, retrieval practice, and self-explanation). Lastly, we included a simple five-step problem-solution structure—where the different phases of the solutions were clearly separated into (1) coding, (2) diagram, (3) physics model, (4) mathematical procedures, and (5) reflection—to scaffold students' self-explanation activities and to help them discover the deep structure of problem-solutions. Hence, the intervention study in paper III included elaborative encoding, retrieval practice, and self-explanations as the main learning strategies; and the elaborative encoding-questions, the Hierarchical Principle Structure for Mechanics, and the problem-solution structure as the main scaffolding tools.

1.1 Motivational background

The main goal of physics education is that our students become able to solve complex problems by modeling situations with physics principles (Burkholder et al., 2020; Docktor et al., 2012; Hestenes, 1987; Hestenes, 2006; Zhu & Wang, 2017). However, many physics students treat physics problems as math problems, searching for equations that match the surface features or the explicitly stated concepts in the problem text (Chi et al., 1981; Mason & Singh, 2016; Walsh et al., 2007). Many students can solve standard problems by using a mathematical approach, despite having low conceptual understanding (Hestenes et al., 1992; Vanheuvelen, 1991; Walsh et al., 2007).

To achieve proficiency in physics modeling, our students must reach a deep understanding of physics principles. However, most students have persistent misconceptions and lack of conceptual knowledge after finishing a physics course, as evidenced by low scores on conceptual tests (Eaton et al., 2019; Halloun & Hestenes, 1985; Kim & Pak, 2002; Wells et al., 1995).

In order to overcome these problems, we want our students to become self-regulated users of effective learning strategies—planning, monitoring, and controlling their learning processes—who knows what to do when, why, and how to do it (Dignath & Veenman, 2020; Veenman et al., 2006). However, students, including physics students, tend to prefer ineffective strategies to effective strategies (Blasiman et al., 2017; Kornell & Son, 2009; Logan et al., 2012; Tullis et al., 2013). There are also many widespread misconceptions many students hold about learning, which favor the use of ineffective strategies (Bjork et al., 2013; Kornell & Son, 2009; Yan et al., 2016).

To get our students to use learning strategies at the right time and in the right way, we first need to understand the knowledge structure they must learn. Basic cognitive science can provide us with important insights into domain-general knowledge types and knowledge structures (e.g. Anderson et al., 2004; Anderson & Schunn, 2000; Hopper & Huber, 2018), while physics education research can help us fill in the domain-specific details (e.g. Chi et al., 1989; Chi et al., 1981; Hestenes, 1987; Larkin et al., 1980; Mestre et al., 1993). For example, students need meaningful associative links within principles and between principles (Anderson & Schunn, 2000; Hopper & Huber, 2018; Markant, 2020); strong memories of physics principles (Anderson et al., 2004; Anderson & Schunn, 2000); hierarchical cognitive structuring of principles (Anderson & Schunn, 2000; Ericsson & Kintsch, 1995; Hardiman et al., 1989; Markant, 2020); abstract declarative rules that provide context, direction, and depth to problem-solving examples (Anderson et al., 1997; Chi et al., 1989); and knowledge of and skill in physics modeling (Antonenko et al., 2011; Hardiman et al., 1989; Hestenes, 1987; Mason & Singh, 2011; Wells et al., 1995).

However, there is a gap between basic cognitive science and educational practice (Anderson & Schunn, 2000; Biwer et al., 2020; Brandmark et al., 2020). A potential way to bridge the gap is to match proven effective learning strategies and scaffolding tools to each aspect of the knowledge structure (Koedinger et al., 2012): Elaborative encoding can be used to construct meaningful associative links within and between physics principles (Anderson & Reder, 1979; Bradshaw & Anderson, 1982; Karpicke & Smith, 2012; Stein et al., 1984); retrieval practice can be used to create strong memories of physics principles (Hopper & Huber, 2019; Pavlik & Anderson, 2008; Rowland, 2014); a visual hierarchical structuring of physics principles, together with elaborative encoding and retrieval practice, can be used to promote a hierarchical cognitive structuring of principles (Ericsson & Kintsch, 1995; Gjerde et al., 2020); self-explanation can be used to create abstract declarative rules (see sections 2.1 and 2.2) that provide context, direction, and depth to worked examples, conceptual knowledge required to do physics modeling (Badeau et al., 2017a; Chi et al., 1989; Renkl et al., 2013); and a structured method of solving problems—clearly separating and explicating physics modeling—can be used to promote knowledge of and skill in physics modeling (Hestenes, 1987; Lee et al., 2017; Mestre et al., 1993; Wells et al., 1995).

Further, there are theoretical and empirical reasons to believe that learning of more basic knowledge potentiates learning of more complex knowledge. Associative links within and between principles can potentiate retrieval practice (Antony et al., 2017; Bradshaw & Anderson, 1982; Hopper & Huber, 2018; Hopper & Huber, 2019; Pavlik & Anderson, 2008); stronger memories of principles can potentiate more complex learning when those principles are constituent knowledge pieces (Reder et al., 2016; Shen et al., 2018), e.g. during self-explanation (Wong et al., 2002) and problem-solving (Anderson & Fincham, 2014; Anderson et al., 2014); hierarchical cognitive knowledge structures can improve working memory performance and retrieval capabilities (Chase & Simon, 1973; Ericsson & Kintsch, 1995), perhaps also helping students understand the structure of the domain knowledge (Markant, 2020); and the abstract declarative rules constructed during self-explanation can potentiate learning from problem-solving (Aleven & Koedinger, 2002; Anderson et al., 1997; Chi et al., 1989). Indeed, almost all instructional methods are heavily moderated by other factors, such as differences in implementation or students' prior knowledge and ability (Lee & Anderson, 2013; Schneider & Preckel, 2017).

Most students lack either the metacognitive knowledge, the motivation, the self-regulation, or even the capacity to ensure that they learn all aspects of the cognitive knowledge structure effectively. Structured learning arenas like lectures, problem-solving seminars, and workshops present us with an opportunity. By integrating the learning strategies into structured learning arenas, also providing associated scaffolding tools and resources, we ensure that most students get exposure and practice with every strategy.

The focus in higher education in Norway has been shifting towards the students as the central actors in learning. Education is now thought to be part of a process of life-long learning (Ministry of Education and Research, 2011) and it is expected that the students are included as active learners in a knowledge construction process (Ministry of Education and Research, 2017). Teaching students effective learning strategies is crucial for facilitating their life-long learning. By integrating effective learning strategies into lectures, we make those lectures more active and more effective. However, direct lecturing still has its place, especially for revealing what is hidden or obscure to the students (Lee et al., 2011; Lee & Anderson, 2013).

2. Theoretical background

When we attempt to affect and explain educational outcomes in physics, we implicitly choose between processes that happen on time scales of different orders of magnitude (Anderson, 2002). Newell (1990) referred to different *bands of cognition*: The *biological band*, involving processes of organelles, neurons, and brain circuits, spans approximately 100 microseconds to 10 milliseconds. The *cognitive band*, involving processes of deliberate acts up to unit tasks (e.g. retrieving an equation and calculating an answer), spans approximately 100 milliseconds to 10 seconds. The *rational band*, involving task processes (e.g. using learning strategies), spans approximately minutes to hours. Finally, the *social band*, such as when attending a physics course, spans days to months.

To realize the full potential of physics education, we must attend to all four bands of cognition (Anderson, 2002; Koedinger et al., 2012). However, the work in this thesis has mainly been focused on bridging the middle two bands, the cognitive and the rational, with the purpose of increasing the time physics students spend engaged in effective learning processes, pursuing meaningful learning goals. This work has also involved interventions that lasted from hours to months. Hence, we have needed to use insights from motivational and sociocultural research in choosing instructional methods, see section 2.4, but this has not been the main focus of our research. Since 2010, physics education research has increasingly been focused on sociocultural aspects (Odden et al., 2020), which has resulted in many important advances. Incorporating these findings was outside the scope of this thesis and must be attended to in future work. Using insights from research on biological processes was also outside the scope of this thesis.

Hence, the following subsections discuss different time scales, or levels, of students' learning and performance (Anderson, 2002). Section 2.1 discusses processes of learning and performance on orders of magnitude of tens of milliseconds to seconds. Meaningful tasks, such as constructing a physics model for a problem, involve tens or hundreds of these unit processes. Section 2.2 discusses the desired educational outcomes in terms of the different aspects of knowledge students need to acquire. Section 2.3 discusses learning strategies, which function on orders of magnitude of minutes to hours. These learning strategies stimulate different cognitive processes and result in different types of knowledge. Section 2.4 discusses interventions in students' use of learning strategies, which involves processes from hours to months. However, even processes at these time scales can be informed by the cognitive processes from section 2.1.

2.1 ACT-R

Adaptive Control of Thought—Rational, ACT-R, is a cognitive architecture that models human cognition (e.g. Anderson, 2007; Anderson et al., 2004; Anderson & Lebiere, 1998). ACT-R, and its mathematical equations, has been used to precisely model well-known phenomena such as the power law of learning (Anderson et al., 1999), the spacing effect (Pavlik & Anderson, 2005), and the fan effect (Anderson & Reder, 1999). More importantly, its mathematical equations for learning and performance have been empirically tested on many learning tasks, such as in cognitive tutors for mathematics and programming, with great accuracy and success (Aleven & Koedinger, 2002; Anderson et al., 1995; Ritter et al., 2007). The theory is widely cited and is sometimes used to explain results in research on learning strategies (e.g. Aleven & Koedinger, 2002; Chi et al., 1989).

Because ACT-R describes human cognition, it describes and constrains the cognitive processes underlying learning strategies, both learning processes and performance. It can be used to compare and contrast learning strategies, to evaluate claims about different strategies, to classify them according to the types of knowledge they produce, and to match strategies to different purposes. Hence, the mathematical equations for describing learning and performance in ACT-R, the implications of those equations, and its descriptions of types of knowledge have all influenced the ideas and interventions in this thesis.

A fundamental idea of ACT-R is the division of knowledge into *declarative* and *procedural knowledge*. A unit of declarative knowledge is called a *chunk*, e.g. “force is equal to mass times acceleration” or “kilogram is the unit of mass”, and is the explicit knowledge you can consciously access and verbalize. A unit of procedural knowledge is called a *production* (procedural knowledge is also called skill), e.g. “IF the goal is to calculate the reactant force, THEN retrieve Newtons’ Third Law” and “IF you need an equation and Newtons’ Third Law has been retrieved, THEN write Newtons Third Law” (simplified examples), and is the implicit, unconscious knowledge in everything you do. For example, you can probably type words without looking at the keyboard while you would struggle with explicitly remembering the location of each letter. Retrieval is the connection between procedural skill and declarative memory, as we retrieve information when it is needed for what we are doing or thinking. This retrieval is controlled by the activation of the declarative chunks (Anderson & Lebiere, 1998), as described in the equations under. Solving any physics problem requires tens or hundreds of productions and retrieved chunks. Hence, ACT-R decribes learning as many small steps, i.e. learning one chunk and one production at a time, and not as a sequence of impasses and great insights (Anderson & Schunn, 2000).

Chunks of concrete knowledge can be encoded through our senses, i.e. passively, such as in lectures or when reading. Chunks of abstract knowledge can be created with our minds (Anderson & Lebiere, 1998), i.e. actively (the action side of productions), such as when trying to find connections between physics principles, when trying to understand a worked example, or when trying to understand what is being said in a lecture. Productions—procedural knowledge—are learned through action, i.e. trying to solve problems of different kinds. We learn new productions by using domain-general productions to interpret retrieved declarative representations of the skill, e.g. interpreting explicit memories of prior studied worked examples with a production similar to “IF the goal is to solve a problem and you have retrieved a similar example, THEN set a goal to map that example to this problem”. The process of learning-by-doing is called compilation in ACT-R (Taatgen & Anderson, 2002). It is a process of gradually mapping perceptions directly onto actions (Taatgen, 2013).

Productions that follow each other get collapsed into single productions, eliminating deliberation in exchange for efficiency (Anderson, 2007). An example would be collapsing the two example productions above into “IF the goal is to calculate the reactant force, THEN write Newtons Third Law”. However, procedural learning is slow and requires plenty of repetition, while declarative learning is a much faster process (Anderson et al., 1997; Taatgen, 2013).

A thorough description of procedural knowledge is outside the scope of this thesis. To briefly describe the performance of procedural knowledge: Productions are subconsciously chosen based on what is in the current goal (small grain size). They respond to what is in the current goal, they usually entail retrieval of declarative knowledge, and they can change the current goal state, either creating, removing, keeping, or modifying a goal. A typical sequence is first the goal match, then declarative retrieval, and then a transformation of the goal. In simplified terms, the goal can be thought of as what is currently in attention (e.g. 2+3=?) and the elements in the current goal can be thought of as the contextual cues (e.g. “2”, “+”, ”3”, and “=”). Often, several productions will match the goal (e.g. productions related to retrieval of the answer or counting on fingers) but only one wins out through a subconscious estimation of the expected utility of each production, which is a function of the expected probability of achieving the goal, the value of the goal, and the expected cost (in time) (Anderson et al., 2004; Anderson & Lebiere, 1998).

The focus in the thesis and in this section is on declarative memory. Procedural problem-solving skills come from abundant practice in problem-solving (Anderson et al., 1997; Koedinger et al., 2012). Moreover, in theory, and as shown empirically, errors in problem-solving are usually errors of retrieval whenever performance is dependent on retrieval of declarative chunks (Anderson & Fincham, 2014; Anderson & Lebiere, 1998; Anderson et al., 1996), which is almost always in physics. A basic assumption in this thesis is that instructors should rather ensure that students acquire a rich store of relevant and prerequisite declarative knowledge to compile during problem-solving. If we fail to ensure this, many students will tend to learn shallow procedural knowledge (Aleven & Koedinger, 2002; Anderson & Fincham, 1994), i.e.

procedural knowledge of formula-hunting without conceptual knowledge, and many will complain that the more complex exam questions were unfair and unlike anything they trained on.

ACT-R includes equations of the dynamics of learning and performance, which can be used in quantitative modeling of different tasks. No quantitative modeling has been done in this thesis. This thesis has rather drawn on these equations as learning principles that explain and constrain learning, using them for qualitative modeling. Only the most relevant equations for the learning and performance of declarative knowledge (Anderson, 2007; Anderson et al., 2004; Anderson & Lebiere, 1998) are presented here. I shortly discuss each equation's meaning and its implications for the thesis. All these equations have been tested empirically.

The most important equation is the activation equation, which describes how active a chunk is:

$$A_i = B_i + \sum_j W_j S_{ji}, \qquad (1)$$

where A_i is the activation of chunk i, B_i is the base-level activation, W_j is the attentional weighting of the elements in the current goal, and S_{ji} is the strength of association from element j to chunk i. The base-level activation is a context-independent estimate of the need for the chunk, determined by its recency and frequency of need, see equation 4. The attentional weighting of the elements in the goal can be thought of as the proportion of your attention allocated to different cues in the context, see equation 5. The associative strengths are estimates of the likelihood that the chunk is needed given that the cue you are currently focusing on is in the context, see equation 6. The sum of the attentional weightings and associative strengths reflect the relevance of the chunk to the current context. The accessibility of a chunk is a function of the activity, given by equation 1, through the retrieval probability equation:

$$Probability = \frac{1}{1+e^{\frac{-(A-\tau)}{s}}}, \qquad (2)$$

where s is the noise in the activation, reflecting temporary and permanent variations in brain activation, and τ is the activation threshold, analogous to the threshold potential of neurons. The speed of retrieval is given by the retrieval time equation:

$$T_i = Fe^{-A_i}, \quad (3)$$

where T_i is the retrieval latency and F is a latency factor. These three equations express that there are two main ways to increase the accessibility and fluency of memories: Base-level strength and associative strength. Equation two tells us that there is an activity threshold that needs to be surpassed for retrieving the memory. The probability of retrieving the memory is 50% at the activation threshold, with the probability getting progressively closer to 100% with increasing activity. Students experience whether they are able to retrieve a memory, not the increase in base strength nor the associative strength from cues to memory. Equation 3 tells us that when a chunk is more active, thinking becomes faster. Retrieval latency at the activation threshold is about .35s (Anderson et al., 2004) and goes down with increasing activity.

The base strength of a chunk is described by the base-level learning equation:

$$B_i = \ln(\sum_{k=1}^{n} t_k^{-d}), \quad (4)$$

where t_k is the time since the k^{th} encounter or retrieval, n is the number of times the item has been encountered or retrieved, and d is the decay rate (average ~ 0.5). The base strength is a context-independent estimate of the need for a chunk, e.g. the high general need for remembering Newtons' second law vs the low general need for remembering the moment of inertia for a pyramid. We can see from equation 4 that the base-strength is determined by the recency and frequency of exposure or retrieval of the chunk and that it is both cumulative and decaying. The decay rate, *d*, of each exposure seems to be higher when the lag between exposures is shorter and lower when the lag is long (Pavlik & Anderson, 2005), giving rise to the well-known spacing effect. Equation 4 is somewhat simplified because, in reality, retrieval adds more strength to a chunk than restudy (Hopper & Huber, 2018; Hopper & Huber, 2019; Kornell et al., 2011; Pavlik & Anderson, 2005). An implication of equation 4 is that we can use structured and distributed retrieval practice to increase the base strength of important memories. Exposure through regular study also increases the base strength but students get little exposure to many of the important physics principles without structured practice. Structured retrieval practice can get the memories of important physics principles above the retrieval threshold so that they become salient and used during self-study. One can see from equation 1 that a higher base strength makes memories less dependent on contextual cues. Therefore, it can also improve transfer to new contexts (Butler, 2010; Carpenter, 2012; Pan & Rickard, 2018; Rohrer et al., 2010).

The attentional weighting of the elements in the goal is given by the attentional weigthing equation (Lovett et al., 2000):

$$W_j = \frac{W}{n}, \tag{5}$$

where W_j is the attention on goal element j, W is the individual's limit on source activity (activation spreading from the goal elements currently in attention) corresponding to working memory (Lovett et al., 2000), and n is the number of elements in current the goal. Equation 5 tells us that there is a limit on the amount of source activity one can get from the context. It implies that it is more difficult to retrieve relevant memories when task complexity (n) increases or when working memory (W) is low. This also implies that high base strength makes individual differences in working memory relatively less important while low base strength makes individual differences in working memory relatively more important (Lovett et al., 2000).

The associative strength from element j in the context to chunk i is given by the associative strength equation:

$$S_{ji} = \ln\left(\frac{prob(i|j)}{prob(i)}\right), \tag{6}$$

where $prob(i|j)$ is the probability that chunk i is needed given that j is in the goal (context) and $prob(i)$ is the base probability that chunk i is needed. The equations for the learning of associative strengths involves Bayesian updating of probabilities and are not presented here. In short, the associative strength, S_{ji}, reflects the log-likelihood ratio that chunk i is needed when element j is in the goal, e.g. the likelihood that F=ma is needed (i) increases substantially when the concept of force (j) is in the current goal. With accumulating experience, the associative strength gets progressively closer to the true probability (Anderson & Lebiere, 1998). Equation 6 implies that a chunk gains less activity from the context when the contextual element is associated with more chunks, i.e. the more associative relationships to facts you have for the concept of force the more difficult it becomes to retrieve any one of those facts on the basis of force as a retrieval cue. This is the well-known fan effect (Anderson & Reder, 1999)—interference due to competing associative links to the concept in attention—which implies that the base strength of key memories becomes progressively more important the more you (are required to) know (Anderson & Schunn, 2000).

2.2 The cognitive knowledge structure for physics principles

Specifically focusing on physics principles, equations 1-6 above imply that students need to construct predictive associative links for physics principles and build the base strength of the memories of principles. Further, there is research to suggest that a hierarchical structuring of the memories can extend working memory capacity by enabling direct encoding into long-term memory (Chase & Simon, 1973; Ericsson & Kintsch, 1995).

The most important associative relationships the students must learn in physics courses are the most predictive relationships for solving problems. However, the only associative relationships the students learn are those they attend to. Therefore, it is crucial that students learn to attend to the deeper features such as principles, conditions of application, and goals in worked examples, features that are usually not explicitly given.

There has been a lot of research on how students learn from worked examples, much of it conducted in physics education. It has been shown that studying worked examples is more effective than problem-solving at the beginning of acquiring cognitive skills (Kalyuga et al., 2001; Renkl, 2014; Sweller, 2006; Zhu & Simon, 1987). When studying a worked example, we can store direct memories of the problem-solving steps or create abstract declarative rules for problem-solving actions (Anderson et al., 1997). An important distinction is that an abstract declarative rule for problem-solving is not the same as procedural knowledge. Although they are easier to interpret than direct memories of examples, these declarative rules must still be retrieved, interpreted, and compiled into procedural skills through sufficient problem-solving practice. In physics, the best learners create highly predictive abstract declarative rules centering on physics principles (Chi et al., 1989; Renkl, 1997).

The main goal of physics education is the development of physics students who can use physics principles to model situations and solve complex problems. A physics model can be viewed as a way to represent the structure in a system (Hestenes, 2006). There are many advanced methods for teaching problem-solving strategies to physics students (Burkholder et al., 2020; Heller & Reif, 1984; Hestenes, 1987; Wells et al., 1995), all involving complex guidelines for how to do physics modeling based on studies of physics experts. The problem-solving process I designed in the early parts of the Ph.D., see appendix 7.3, was similar to these approaches. The relatively simple idea of physics modeling can get lost in all these details. Moreover, ensuring high student adoption of these problem-solving strategies require substantial time and resources on the instructors' part and substantial motivation and belief on the students' part. In paper III, we rather used the simple approach of defining physics modeling as an attempt to describe the situation with physics principles, clearly separating the physics model from the mathematical procedures in the solutions and clearly naming them thus. The assumption was that the most important step was to make students aware of physics modeling. What experts do intuitively may be too advanced for novice students. One also has to consider what is feasible for physics instructors to implement.

In sum, this research project has aimed to facilitate students' learning of physics principles for the five important aspects of the cognitive knowledge structure mentioned above: (1) Meaningful associative links within- and between principles, (2) strong memories of principles, (3) a hierarchical structuring of the knowledge, (4) highly predictive abstract declarative rules, and (5) knowledge of physics modeling. These five aspects are not easily dichotomized into a surface approach or a deep approach to learning (e.g. Asikainen & Gijbels, 2017). They are more easily categorized from basic to complex and they are all essential to achieving mastery. Our approach has been to facilitate efficient learning of all these aspects of the cognitive knowledge structure by explicating the knowledge structure, making students more aware of the learning strategies, modeling the learning processes, facilitating practice, and designing scaffolding resources. Further, efficient learning on the more basic levels, e.g. elaborative encoding and retrieval, facilitate learning on the more complex levels (Alexander, 2003; Alexander et al., 1997; Reder et al., 2016), e.g. constructing abstract declarative rules and physics modeling, making it more likely that students adopt the more complex practices.

2.3 Learning Strategies

Learning strategies (Donker et al., 2014), also called learning techniques (Dunlosky et al., 2013) and study strategies (Blasiman et al., 2017), are specific methods for acquiring knowledge and skills. Cognitive science and educational psychology have shown that some learning strategies are more effective than others (e.g. Donker et al., 2014; Dunlosky et al., 2013; Roediger & Pyc, 2012). Further, different learning strategies affect different aspects of the knowledge structure. Therefore, we can bridge the gap from cognitive science and educational psychology to educational practice by matching appropriate learning strategies to the different aspects of the cognitive knowledge structure (Koedinger et al., 2012).

The focus of this thesis has been to improve students' knowledge and use of physics principles. We have defined *physics principles* as being both the fundamental principles (Newtons' three laws and conservation of energy) and the derivable principles (e.g. impulse-momentum theorem), excluding those equations that can be classified as definitions (e.g. p=mv). In other words, we have basically treated all the equations in the Hierarchical Principle Structure for Mechanics as physics principles, see appendix 7.4, although some equations at the bottom are better classified as definitions. We have defined *physics modeling* as attempts to describe physical situations in textbook problems (although the idea also applies to other situations) with the use of physics principles in a way that is sufficient to solve a given problem while being cognizant of the conditions of application of the principles. This can be contrasted with the practice of formula-hunting, where students search for equations that match the given variables and goal variables and plug-and-chug the numbers. The term *conceptual knowledge* is basically what is measured by conceptual knowledge tests, which test students' ability to qualitatively understand what happens in situations by thinking in terms of physics principles, minimizing or removing the need for mathematics. This is related to the ability to do physics modeling, with physics modeling adding a layer of mathematical complexity. Finally, we want our physics students to *understand* physics principles. Understanding can be defined by ACT-R as having richly interconnected and highly accessible chunks (declarative knowledge) together with plenty of flexible productions (procedural knowledge) that can be used to solve problems (Anderson & Schunn, 2000).

Elaborative encoding

Elaborative encoding is the targeted creation of associative connections between chunks (S_{ji} in equation 1). It has been shown that it increases the probability of retrieval success through redundancy of cues and redundancy of ways to infer the target memory (Bradshaw & Anderson, 1982) and that it works best when the associative links are meaningful, predictive, plentiful, and integrated (Anderson & Reder, 1979; Bradshaw & Anderson, 1982; Stein et al., 1984). Elaborative encoding mainly affects the S_{ji} terms in equation 1 by increasing the quantity and quality of the associative connections. For example, when elaboratively encoding Newtons' Second

Law one may find associative connections within the principle by finding connections between the concepts and units, constructing concrete examples, representing the equation graphically, or imagining what happens if the size of one variable change. One can also find associative connections between physics principles, e.g. to conservation of linear momentum, the work-energy theorem, or Newtons' second law for rotation. Hence, elaborative encoding, when properly implemented, is to build richly interconnected and highly accessible chunks related to concepts and principles, i.e. the declarative aspect of understanding. Elaborative encoding is what we want our students to do when they study the conceptual aspects of physics, whether individually or in groups. With the right task structure and appropriate instructional material, one can also facilitate a hierarchical structuring of the students' knowledge through elaborative encoding. Further, elaborative encoding can give students practice in translating between different types of representations of physics principles, an important ability during physics modeling (Hestenes, 1987; Hestenes, 2006).

Elaborative encoding potentiates retrieval practice, as retrieval practice becomes more efficient with a higher retrieval success percentage (Eglington & Pavlik Jr, 2020; Pavlik & Anderson, 2008; Racsmány et al., 2020). Conversely, retrieval practice also potentiates new encoding (Chan et al., 2018; Grimaldi & Karpicke, 2012; Pastotter & Bauml, 2014; Pastotter et al., 2011; Reder et al., 2016), meaning that the two strategies are synergistic.

I know of no research specifically using elaborative encoding for learning meaningful and predictive relationships within- and between physics principles. However, there have been positive results in research on concept mapping in physics (Martinez et al., 2013; Pankratius, 1990; Zieneddine & Abd-El-Khalick, 2001), which has similarities to elaborative encoding.

Retrieval practice

> A curious peculiarity of our memory is that things are impressed better by active than by passive repetition. I mean that in learning (by heart, for example), when we almost know the piece, it pays better to wait and recollect by an effort from within, than to

> look at the book again. If we recover the words in the former way, we shall probably know them the next time; if in the latter way, we shall very likely need the book once more. William James (1890, p. 646)

The effectiveness of retrieval practice was discussed already in 1890 and has probably been the most researched learning strategy since. It is also probably the learning strategy with the most positive evidence for its efficacy in improving students' memory for facts and relationships (Chan et al., 2018; Dunlosky et al., 2013; Roediger & Pyc, 2012; Rowland, 2014). However, very little research has been done on retrieval practice in physics learning and instruction (Zu et al., 2019).

Retrieval practice is targeted recall of facts and relationships to improve the accessibility and durability of memories. In ACT-R terms, retrieval practice improves the base strength of memories, see equation 1 and 4. It has consistently been shown that retrieval practice is more effective than re-studying (Rowland, 2014), especially when the retrieval practice is spaced out and the retention interval is long (Latimier et al., 2020). Retrieval practice adds more base strength (B_i in equation 1) to a memory than restudy (Kornell et al., 2011). Unlike restudy, retrieval practice promotes reconstruction of the memory, strengthening intra-principle associative links (Hopper & Huber, 2018; Hopper & Huber, 2019). However, this requires that meaningful associative links have already been constructed. One could also do rote rehearsal of the surface structure of principles, repeating its symbols and letters to oneself without creating meaningful connections. However, this is less effective (Robey, 2019).

As implied by equation 5, there are strong limitations on the amount of neural activity that can be stimulated by contextual cues (Anderson et al., 1996; Lovett et al., 2000). Memory strength does not share this limitation. Therefore, retrieval practice should improve performance for physics problems of high complexity, especially for individuals with low working memory (Agarwal et al., 2017; Lovett et al., 2000; Reder et al., 2016; Shen et al., 2018). Stronger memories also directly affect the learning of more complex knowledge when those strong memories are constituent pieces (Reder et al., 2016; Shen et al., 2018).

Research with fMRI has shown that the planning phase of problem-solving is characterized by large amounts of brain activity in areas related to retrieval and metacognition (Anderson & Fincham, 2014; Anderson et al., 2014; Lee et al., 2014), with the metacognitive activity driving a significant amount of the retrieval activity and the amount of metacognitive activity associated with achieving mastery (metacognitive activity is roughly defined here as reflecting on declarative knowledge). When solving physics problems, this would probably mean retrieving relevant physics principles and other types of domain knowledge and describing the situation using these principles, i.e. physics modeling. Ibrahim et al. (2017) argue that the main reasons for students' failure to identify relevant concepts for solving complex, multi-principle problems are lack of familiarity and low confidence in the principles. Indeed, when problem-complexity increases, a large proportion of failures in problem-solving are caused by misretrievals (Anderson et al., 1996).

In sum, acquiring strong memories of physics principles is a necessary step on the way to physics modeling mastery. Spaced retrieval practice is the best way to build lasting base strength of physics principles, see equation 1 and 4. However, its efficacy also depends on having meaningful associative links within and between physics principles, which can be constructed with elaborative encoding. With appropriate instructional material, one can also facilitate hierarchical structuring of the students' knowledge through retrieval practice.

Self-explanation

Worked examples—pre-made solutions to problems containing the problem formulation, the necessary steps to solve it (with or without instructional explanations), and the final solution—are essential for efficient learning of cognitive skills (Anderson & Fincham, 1994; Lee & Anderson, 2013; Renkl, 2014). Self-explanation is an especially effective learning strategy for learning from worked examples (Badeau et al., 2017a; Bisra et al., 2018; Chi et al., 1989; Renkl, 1997). *Self-explanation* is to try to explain the steps in worked examples to oneself to improve ones' understanding of the example and to increase the likelihood of being able to solve similar problems in the future. When self-explaining, the student constructs abstract declarative rules that can be retrieved and interpreted during problem-solving (Anderson et al., 1997; Chi et al., 1989; Gjerde et al., in review). Abstract declarative rules are declarative representations of procedural skills and must still be retrieved and interpreted during problem-solving.

The most important associative relationships students must learn in physics courses are the most predictive relationships for solving problems. However, the only associative relationships the students learn are those they attend to. Good instruction biases students to discover correct rules and principles (Lee et al., 2016). Hence, it is crucial that students learn to attend to the deeper features such as physics principles, conditions of application, and goals, features that are usually not explicitly given in worked examples. Solving a complex problem requires tens or even hundreds of small knowledge and skill units (Anderson & Lebiere, 1998; Anderson & Schunn, 2000). When students lack too many of these knowledge and skill units, they are not able to bridge the gaps during problem-solving, thereby failing to solve the problem. Worked examples provide support for filling those gaps by supplying relevant actions and outcomes that can be explained and understood (Koedinger et al., 2012).

The most difficult part of solving complex problems in mechanics is usually not the math; it is to set up a physics model, i.e. determining what physics principles apply, which of these principles accurately describe the situation, which of these principles are sufficient for solving the problem, and how to set up these principles. Self-explanation of worked examples facilitates construction of the conceptual knowledge required for physics modeling. Further, declarative representations of procedural actions increase the likelihood that students build accurate, as opposed to shallow and inaccurate, procedural skills (Aleven & Koedinger, 2002).

Self-explanation increases students' reliance on prior knowledge (Williams & Lombrozo, 2010, 2013). Wong et al. (2002) found evidence that the effects from self-explanations were mediated by knowledge generation—which is what happens when one constructs declarative abstract rules—and that knowledge generation was predicted by prior knowledge (as measured by a pretest) and knowledge access (measures of students' retrieving prior knowledge). This implies that, for self-explanation to be effective, one needs relevant prior knowledge with high base strength. When students explain using domain knowledge, such as physics principles, these memories get further strengthened and elaboratively encoded (Aleven & Koedinger, 2002; Anderson et al., 2004). In other words, self-explanation may synergize with retrieval practice and elaborative encoding.

Self-explanation has been shown to be effective for learning physics (Badeau et al., 2017b; Chi et al., 1989). However, training interventions with self-explanation have had mixed success (Aleven & Koedinger, 2002; Bielaczyc et al., 1995; Conati & Kurt, 1999; Renkl et al., 2013; Wong et al., 2002), although none have had negative effects. Aleven and Koedinger (2002) added self-explanation to an already successful cognitive tutor for geometry, which was based on the ACT-R theory. The self-explanation group learned with greater understanding, had higher success on hard problems, and reflected more on the sufficiency of their knowledge. Renkl et al. (2013) did a short training intervention where only a few students adopted the strategy. They suggested that future training interventions needed to be longer and the treatment stronger. Conati and Kurt (1999) designed a self-explanation coach to scaffold physics students' self-explanations. The lack of positive results seemed to be due, in part, to insufficient scaffolding for creating high-quality self-explanations and the high cognitive load due to dialog boxes. They also suggested that future training interventions needed to be longer and the treatment stronger. The studies imply that self-explanation training can have positive effects, even compared to already highly successful treatments as in the study by Aleven and Koedinger (2002), but that interventions need to have a strong and lasting treatment.

2.4 Facilitating use of learning strategies

Some instructional methods, such as *modeling*, *prompting* or *cueing*, and *embedding* strategy use in instruction have been shown to enhance students' use of learning strategies (Dinsmore, 2018). Many of these instructional methods can also be understood in terms of ACT-R. A student that learns to use a new learning strategy must first get declarative knowledge of how to use the learning strategy. Modeling the use of the strategy is an effective way to give students examples that they can emulate, i.e. retrieve and interpret. However, retrieving memories of examples of strategy use is not easy because of the low base strength and lack of predictive associative cues. Prompting or cueing the students to use the strategy can help them remember or tell them what to do. In general, *scaffolding* resources give temporary support to students in the early phase of learning a new strategy (Wood et al., 1976). They may achieve this purpose by giving external aid for accessing the relevant declarative knowledge of how to use the learning strategy or by organizing the instructional material that the students are supposed to use the learning strategy on, generally reducing the cost of engaging in a strategy. However, it is not enough to give students examples of how to use the strategy. They must also be given ample opportunity to practice using them before the declarative memories decay and become too difficult to retrieve. Practice both improves the base strength of their declarative memories and compiles their declarative knowledge into procedural skills, making it easier to use the strategy in the future, i.e. improving the probability of success and reducing the cost. A way to ensure that students practice using the learning strategies and that they learn to use them on relevant material is to embed learning strategy interventions into instruction. There is a growing consensus that embedding is superior to strategy interventions outside the context of the classroom (Dignath & Veenman, 2020; Hattie et al., 1996; Tricot & Sweller, 2014). In ACT-R terms, this also ensures that their knowledge of how and when to use the strategies gets connected to cues that are likely to be in the relevant context.

When students need to be self-regulated users of learning strategies, outside the context of structured learning arenas, there are additional important considerations to make. *Self-regulation*—planning, monitoring, and controlling ones learning processes—is strongly predicted by a students' personality, especially conscientiousness (de la Fuente et al., 2020), and is probably difficult to change. We can, however, facilitate improvements in students' *metacognitive knowledge* of the learning strategies, i.e. their knowledge of interactions between themselves (e.g. prior knowledge), the learning task (e.g. problem-solving), and the learning strategies

(Flavell, 1979; Veenman et al., 2006). A useful framework for thinking about metacognitive knowledge is WWW&H (Dignath & Veenman, 2020; Veenman et al., 2006), knowing What to do When, Why, and How. Students first need to be aware of the strategy and they need to know when to use it. They need to know why they should use the learning strategy; else they have no reason for engaging in it. This is related to the expected gain in ACT-R and value in motivational theory. Finally, they need to know how to do it, which is best taught through modeling and the other instructional methods mentioned above.

There are further important moderators of students' use of learning strategies that we can affect. The students are more likely to engage in complex domain-specific strategies—such as self-explanation and physics modeling—when they have more domain knowledge (Alexander, 2003; Dinsmore, 2018). Their domain knowledge can, for example, be efficiently improved by properly implemented elaborative encoding and retrieval practice. The students' motivation is another important predictor of strategy use (Dinsmore, 2018). There are several well-known frameworks for thinking of students' motivation, such as achievement motivation and goals (Elliot & Church, 1997; Senko, 2019), Self-Determination Theory (Deci & Ryan, 2000), and the Expectancy-Value-Cost theory (EVCT) (Eccles & Wigfield, 2002; Jiang et al., 2018). We have found expectancy (self-efficacy), value, and cost to be especially fruitful constructs for thinking about students' decisions about what to do. Although the constructs determining expected utility in ACT-R refer to decisions of much smaller grain size than in EVCT, there are apparent similarities between the probability of achieving the goal and self-efficacy, between expected value of the goal and value, and between the cost-constructs in the two theories, see section 2.1. Expectancy and value are also thought to interact in EVCT (Trautwein et al., 2012), just as the probability of success and expected gain does in ACT-R (Anderson et al., 2004). Self-efficacy is mainly affected by performance accomplishments (Bandura, 1977). Value is related to metacognitive knowledge of why one should use the learning strategies (Barron & Hulleman, 2014) and is affected by factors such as students' goals and performance experiences (Trautwein et al., 2012). The cost of using the learning strategies can be reduced through the instructional methods described above, such as modeling and scaffolding, and by turning them into procedural habits through abundant practice. It follows from these constructs and how they interact in ACT-R and EVCT that when the students believe that a task is of high value, they can tolerate higher cost and lower probability of success or self-efficacy.

Beliefs about knowledge and learning are also important in students' choices in whether to use learning strategies. Students tend to equate high effort with poor learning and vice versa (Bjork et al., 2013; Kirk-Johnson et al., 2019), which is a large barrier because effective learning strategies are generally more effortful than less effective learning strategies. They also tend to have a stability bias in their beliefs about memory (Kornell & Son, 2009), meaning that they are overconfident in their current knowledge and underconfident in their future learning. These and other misconceptions about learning make it difficult to make students self-regulated users of learning strategies (Yan et al., 2016).

2.5 Aim and research questions

The sections above tell us that there are large research gaps for how to make the teaching and practice of these learning strategies an integral and effective part of physics education. We need to find ways to implement these learning strategies in such a way that our students use them in both structured learning arenas and their self-study. We also need to integrate these learning strategies in such a way that our students' use of them capitalizes on their synergistic effects. Lastly, if we want our interventions to have an impact, we must find ways to make them implementable and desirable for physics instructors.

The overarching aim of this thesis was to create self-regulated physics students who use effective learning strategies, achieve deep understanding of physics principles, and become able to solve conceptually challenging physics problems within the timeframe of a semester-long course. On the way to achieving this aim, we have asked the following research questions:

- Paper I – *Retrieval practice of a hierarchical principle structure in university introductory physics: Making stronger students*:
    - Do students lack knowledge of basic facts and principles after a semester-long course?
    - Can retrieval practice improve scores on a factual knowledge test?
    - Does participation in structured retrieval practice sessions during lectures correlate with factual knowledge and final exam results?
    - Does score on a factual knowledge test predict exam results?
- Paper II – *Problem solving in basic physics: Effective self-explanations based on four elements with support from retrieval practice*:
    - Can retrieval practice of physics principles and their conditions of application improve students' learning from self-explanations?
    - What knowledge representations should students seek to acquire during self-explanation of worked examples?
- Paper III – *Integrating Effective Learning Strategies in Basic Physics Lectures: A Thematic analysis*:
    - What are the students' experiences and associated reflections with the learning strategies and tools?
    - How do the students' experiences and reflections align with established theory on the learning strategies?
    - What main barriers to effective implementation of the learning strategies may be hypothesized?

3. Methods

This chapter describes the methods used in the three papers. First, I describe the research participants. Then, I discuss the measures and their reliability. Next, I discuss the research questions, the associated research designs, and questions of validity. Finally, I briefly discuss the analytical software, effect size interpretations, and ethical considerations. See Table 1 in section 3.4 for an overview of the methods.

3.1 Participants

All the papers were done in the context of an introductory mechanics course at the University of Bergen with approximately 150 students enrolled each year. The participants across the three papers were from different cohorts of this course. Paper I and II involved both experimental and correlational analysis. Therefore, we needed a substantial number of participants to detect effects and associations. The studies were conducted in lectures and were voluntary, so we were limited to the number of students that showed up. There were $N = 81$ participants in phase 1 (2018) and $N = 130$ participants in phase 2 (2019) of paper I. However, the sample size varied between the different quantitative measures in phase 2. There were $N = 57$ participants in study 1 (2018) and $N = 54$ participants in study 2 (2019) of paper II. Paper III was an interview study. Therefore, we were interested in the saturation of themes rather than finding trends and effects. We tried to recruit between 10 and 15 students, which we deemed sufficient and attainable. There were $N = 12$ interview participants in paper III (2020). The students came from a mix of study programs, mostly Energy, Ocean Technology, Physics, Geophysics, Teacher Education, Nanotechnology, and Petroleum Technology.

3.2 Measures and their reliability

The reliability of a measure—how consistently it measures a construct—can be quantified with internal consistency, interrater reliability, and test-retest stability.

We quantified the internal consistency—the interrelatedness of items—with Cronbach's alpha. Cronbach's alpha gives a mean of all possible split-half coefficients for a test (Cronbach, 1951). It assumes unidimensionality and does not measure unidimensionality as is often claimed. Assuming unidimensionality, the alpha does not give an accurate value for reliability but rather something like a lower bound (Sijtsma, 2009). Values of Cronbach's alpha above 0.70 is widely cited as acceptable (Taber, 2018). However, there is no objective level at which the alpha suddenly becomes acceptable. Instruments with low alpha can still be useful (Schmitt, 1996) and interpretable (Cronbach, 1951). Moreover, it is not always desirable that a measure only targets one single construct. In these cases, the assumption of unidimensionality is not met and Cronbachs' alpha is likely to underestimate the reliability of the measure (Cronbach, 1951).

We quantified the interrater reliability with percent agreement and Cohen's Kappa. Unlike Cohen's Kappa, the percent agreement does not take into account chance agreement. The strength of agreement, using Cohen's Kappa, can be interpreted as poor for $\kappa < 0$, slight for $\kappa = .00\text{-}00.20$, fair for $\kappa = 0.21\text{-}0.40$, moderate for $\kappa = 0.41\text{-}0.60$, substantial for $\kappa = 0.61\text{-}0.80$, and almost perfect for $\kappa = 0.81\text{-}1.00$ (Landis & Koch, 1977). However, it seems that most classifications of Kappa-values are somewhat arbitrary and that there is no objective value at which Cohen's Kappa suddenly becomes acceptable (Bakeman et al., 1997). Kappa values also tend to be suppressed when there are few codes and their probabilities are variable (as in paper II).

We did not attempt to quantify any of the measures' test-retest reliability, partly because it was impractical to do so and partly because we expected the students to improve on the tests.

Paper I

The measures in paper I were attendance in retrieval practice, the declarative facts test, prior calculus grade, and final exam grade. The reliability of the measure of *attendance in retrieval practice* was not quantified but was self-evidently high. The declarative facts test used in paper I was self-developed. Cronbach's alpha for this measure was 0.89 and 0.87 in phase 1 and phase 2, respectively. We did not quantify the reliability of either the final exam or the prior calculus grades. However, the practice of final exams rests on an assumption that they are indeed reliable and valid.

Paper II

The measures in paper II were the quantified self-explanation categories, two problem-solving tests, two conceptual tests. The inter-rater agreement for the self-explanation categories in study 1 was 89%, with a Cohen's Unweighted Kappa of 0.85. The inter-rater agreement for the self-explanation categories in study 2 was 91%, with a Cohen's Unweighted Kappa of 0.85.

The problem-solving test in study 1 consisted of one problem from Badeau et al. (2017a) and one self-developed problem that was isomorphic to the first. The problems were scored according to the rubric in Badeau et al. (2017a), with an interrater agreement of 90% and unweighted Cohen's Kappa = 0.76. The Cronbach's alpha for this measure was 0.96. The problem-solving test in study 2 of paper II was self-developed because we tested different concepts than in study 1. The five problems were also scored according to a slightly different rubric, with an interrater agreement of 97% and unweighted Cohen's Kappa = 0.93. The Cronbach's alpha for this measure was 0.87.

The conceptual test in study 1 consisted of three items from the Mechanics Baseline Test (Hestenes & Wells, 1992). The Cronbach's alpha for these items was 0.74. The conceptual test in study 2 was seven items from the Energy and Momentum Conceptual Survey (Singh & Rosengrant, 2003). The Cronbach's alpha for these items was 0.62. Two items were removed to increase Cronbach's alpha to 0.69. However, both of these conceptual tests probe understanding of different concepts within the multidimensional construct of conceptual understanding, so the assumption of unidimensionality was probably not met.

Paper III

In paper III, the intra-rater reliability was ensured by cross-checking the identified themes with the data, searching for a lack in internal homogeneity (coherence within themes) and external heterogeneity (distinguishability between themes) (Braun & Clarke, 2006). In qualitative research, one might also use the term dependability, which is when the analysis is evaluated by others and they agree that, given the data, the findings make sense (Lincoln & Guba, 1985). The analysis was therefore discussed in seminars with the first and last author and three other science education researchers.

3.3 Research questions, design, and validity

This section presents each paper's research questions, the design for answering those questions, and potential threats to the validity of our inferences in each paper. Validity relates to inferences, not designs and methods. Questions of validity are always answered by qualitative judgments of inferences about validity. There is no way to ensure validity. One can only minimize threats to validity, mainly through research design and considering each potential threat to validity in the particular study (Shadish et al., 2001).

Every study is a mix of particular persons, treatments, settings, and outcomes (Shadish et al., 2001). *Construct validity* is a qualitative judgment of inferences of whether these particulars generalize to the abstract constructs they are meant to represent. *External validity* is a qualitative judgment of inferences of whether causal relationships generalize to variations in persons, treatments, settings, and outcomes. *Statistical conclusion validity* is a qualitative judgment of inferences about the existence and strength of the correlation between treatment and outcome. Finally, *internal validity* is a qualitative judgment of inferences of a causal relationship between treatment and outcome (Shadish et al., 2001).

In educational research, there are some common threats to validity. There can often be a tension between internal and external validity, the former improved by strict control of variables, the latter improved by authentic and representative persons, treatments, settings, and outcomes. Typical threats to statistical conclusion validity are low statistical power, as it may be difficult to recruit many participants, and the heterogeneity of the participants, i.e. the large variance in the students' knowledge and ability. Both tend to increase the probability of type-2 errors (accepting the null hypothesis when there is an effect). Finally, students' may not always follow instructions as intended, thereby threatening the construct validity of the treatments.

Paper I

RQ 1.1: Do students lack knowledge of basic facts and principles at the end of a semester-long course?
RQ 1.2: Can retrieval practice of a hierarchical principle structure improve scores on a factual knowledge test?
RQ 1.3: Does participation in structured retrieval practice sessions during lectures correlate with factual knowledge and final exam results?
RQ 1.4: Does score on a factual knowledge test predict exam results?

Design in paper I: Paper I consisted of two phases. In phase 1, we did a randomized controlled trial where one group did 70 minutes of retrieval practice, the other group studied problems, and both groups were tested on a declarative fact test afterward. In phase 2, we did a longitudinal intervention with 15-minute sessions of structured retrieval practice each week. We tested the students on the declarative fact test and collected exam results.

1.1: We qualitatively judged whether the students lacked knowledge of basic facts and principles based on the control groups' average score on the declarative facts test, a qualitative judgment of the difficulty of the test items, and a qualitative judgment of the construct validity of the test. Other researchers and educators should judge whether they agree. We believe that this result is generalizable to introductory mechanics students at other, similar universities, with students of similar background in physics, and without structured retrieval practice. This is also easily testable.

1.2: A randomized controlled trial (RCT) was used to test whether students' memory for basic facts and principles could be improved by retrieval practice compared to studying problems. There are no obvious threats to the statistical conclusion validity or internal validity. We used only one type of measure for students' memory of basic facts and principles, a cued recall test, making cued recall a part of the construct we measured. However, this is more relevant than recognition or free recall tests for improving performance during problem-solving. Considering the large research literature on retrieval practice and that there is nothing blatantly special about our students or the setting, we also feel confident in the external validity of our results. However, the causal relationship may interact with variations in treatment implementation.

1.3: We correlated the number of retrieval practice sessions attended with the score on the final exam and the declarative facts test. The biggest threats to the statistical conclusion validity are potential unreliability of treatment implementation, as we cannot be certain that the students retrieved the items instead of copying or using other suboptimal procedures; extraneous variance from other activities; and the heterogeneity of the students. These threats would likely all lead to underestimation of the effects. We also calculated a multiple regression model with retrieval practice sessions attended, prior calculus grade, and their interaction as predictors for final exam score. This controlled for some of the heterogeneity between students, improving the statistical conclusion validity. However, as pointed out by A.F. Heckler (personal communication, August 24, 2020), the statistical conclusion validity of the interaction effect between attendance in retrieval practice and prior calculus grade could be threatened by a ceiling effect whereby the best students cannot achieve a better grade than A, suppressing the measured effect of retrieval practice for the strong students.

The biggest threats to the internal validity of a claim of a causal relationship from retrieval practice to final exam grade are selection effects and confounding variables. We cannot rule out that there were systematic differences between the students who attended many vs few retrieval practice sessions, i.e. selection effects. However, we have some unpublished data from the spring of 2020, where we found neither motivational nor ability-related (prior calculus grade) predictors of attendance in any of the structured learning arenas in the first seven weeks of the semester. We also cannot rule out that confounding variables were the real causes of the whole or part of the measured effects. For example, the retrieval practice sessions were embedded in lectures. Hence, the effects may have been due to the lecturing. On theoretical grounds, we find this implausible for the effects on the declarative facts test. Causes closer to the outcome will typically be more strongly related to the outcome (Schneider & Preckel, 2017; Shadish et al., 2001), and retrieval practice is closer to the outcome of fact retrieval than the final exam. Although the correlation between retrieval practice and exam results was only slightly smaller than that for score on the declarative facts test, the potential causal effect is more speculative and needs to be corroborated by other results, e.g. the quasi-experimental and experimental effects on problem-solving in paper II.

We see no major threats to construct validity, although that depends on what we claim to have measured. The cause we want to manipulate is memory strength, but attendance in retrieval practice sessions does not ensure that the students improve their memory strength because the students may do nothing. The large experimental effect in phase 1 and the strong correlation in phase 2 with the score on the declarative facts test are indicative of improvements in memory strength. However, this test only measures whether the memory reaches the retrieval threshold, not the memory strength per se (Anderson et al., 2004). A better measure of memory strength would be response latency (Pavlik & Anderson, 2005, 2008), see equation 3, but this would be difficult to implement.

We see no major threats to external validity. However, as mentioned for RQ 1.2, the external validity may be threatened by interactions with treatment variations, e.g. how or when the structured retrieval practice sessions are implemented, and by interactions with the students, e.g. their background knowledge, age, or culture. Relatedly, we discussed the importance of having associative links between principles for potentiating retrieval practice in paper III.

1.4: To see whether scores on a factual knowledge test predict exam results, we calculated the correlation between these variables. We see no major threats to the statistical conclusion validity, construct validity, or external validity. The major threats to the internal validity of a claim of a causal relationship are potential confounding variables, such as prior knowledge and ability.

Paper II

RQ 2.1: Can retrieval practice of physics principles and their conditions of application improve students' learning from self-explanations?
RQ 2.2: What knowledge representations should students seek to acquire during self-explanation of worked examples?

Design in paper II: Paper II consisted of two studies. In study 1, we did a quasi-experimental test of the effects of retrieval practice one week prior to a problem-solving test and a conceptual test. Just before the test, the students engaged in a learning phase where they studied examples. In the learning phase, 18 of the students did written self-explanation of worked examples. These written self-explanations were coded, categorized, and quantified so that we could correlate categories of self-explanation with performance. In study 2, we did a randomized controlled trial with one group doing retrieval practice, the other group self-explaining worked examples, then both groups self-explaning worked examples before being tested on a problem-solving test and a conceptual test. All 55 students in this study did written self-explanations of worked examples and these were again coded, categorized, and quantified so that we could correlate categories of self-explanation with performance.

2.1: To find whether retrieval practice of physics principles and their conditions of application can improve students' learning from self-explanations, we first used quasi-experimental data in study 1 to explore between-group differences on a problem-solving test and a conceptual test. We tried to replicate the effects on problem-solving and conceptual knowledge, using a randomized controlled trial and different physics concepts.

The biggest threats to statistical conclusion validity in both studies were low statistical power; the unreliability of treatment implementation, i.e. that the retrieval practice was probably performed suboptimally by some students; and the heterogeneity of the participants, i.e. that the high variance on the performance tests reduced the effect size.

The biggest threat to internal validity in study 1 was potential selection effects, i.e. that the students who had done retrieval practice were systematically different from the students who had not done retrieval practice. We see no major threats to internal validity in study 2.

The biggest threat to construct validity, especially in study 1 but also in study 2, was construct confounding. We asked the research question of whether retrieval practice of physics principles and their conditions of application can improve students' learning from self-explanations. However, we cannot say for certain whether performance on the problem-solving tests was indirectly affected through potentiated self-explanation or directly affected through improved access to physics principles. As already mentioned, we expected both indirect and direct effects. In study 2, the construct validity may also have been threatened by confounding the construct with the level of the treatment, i.e. that the treatment was too weak to get a measurable effect compared to control.

The biggest threats to external validity are potential interactions with treatment variations, i.e. how the retrieval practice is implemented (modeling, scaffolding, etc.), and potential interactions with the students' prior knowledge and ability.

2.2: To find what knowledge representations students should seek to acquire during self-explanations of worked examples, i.e. what the constructed abstract declarative rules should consist of, we qualitatively coded students written self-explanations according to an a priori theoretical coding scheme, quantified the coded categories, and used correlations and regression analysis to predict the problem-solving score and conceptual score.

The biggest threat to statistical conclusion validity was the low statistical power for detecting smaller relationships, especially in study 1. This also prevented us from exploring more nuances in the data. Both the problem-solving test and the conceptual test in study 2 were structurally more dissimilar from the practice problems (the problems they self-explained) than in study 1, making it more difficult to transfer what they may have learned from self-explaining. This may have led to smaller associative relationships in study 2 than in study 1.

The biggest threat to the internal validity of a claim that specific self-explanation types caused test outcomes is that we do not know whether students had already formed the knowledge representations, whether they formulated them during the self-explanation practice phase, or whether it was a combination. Still, a strong correlation indicates that the knowledge representation is important to acquire somehow.

The construct validity of the self-explanation categories rests on the theoretical background and qualitative coding. We see no major threats to the construct validity of the problem-solving tests or the conceptual knowledge tests. However, the conceptual test in study 2 may have failed to measure the learning effects from the self-explanation.

The biggest threat to external validity is a potential interaction with treatment variations. We chose to make students write self-explanations to enable an analysis of their self-explanations. However, students will probably choose to think or speak their self-explanations during self-study, rather than writing them. Written self-explanations may not generalize to thought and spoken self-explanations. However, we find this threat theoretically implausible.

Finally, the fact that we replicated the results in study 2 with more students, that we elaborated the coding scheme, and that the results aligned with theoretical expectations, improves our confidence in the validity of our claims.

Paper III

(1) What are the students' experiences and associated reflections with the learning strategies and tools?
(2) How do the students' experiences and reflections align with established theory on the learning strategies?
(3) What main barriers to effective implementation of the learning strategies may be hypothesized?

Design in paper III: Paper III was an intervention with multiple learning strategies in an introductory mechanics course.

To answer the research questions, we used thematic analysis of semi-structured research interviews with 12 students. The validity of the analysis depends on the theoretical and analytical approach (Braun & Clarke, 2006), which was laid out in paper III. Validity was ensured through considering whether the themes and thematic maps accurately reflected the entire dataset, cross-checking the identified themes with the data, and searching for a lack in internal homogeneity (coherence within themes) and external heterogeneity (distinguishability between themes. The thematic analysis was also discussed in seminars with the first and last author and three other educational researchers.

Internal validity, or credibility as it is often called in qualitative research, can be assessed by investigating whether the data sources, the participants, find the researchers' interpretations to be credible (Lincoln & Guba, 1985). However, the students are not familiar with the theoretical underpinnings of our analysis, and students are known to often hold opposite views of what empirical research and theory indicate to be true. Therefore, they would be hard-pressed to evaluate the credibility of our analysis. However, the students were interviewed by an interviewer they did not know, reducing the social desirability bias that would be present if they were interviewed by their lecturer or seminar leader. The interviewer generally followed the guidelines for interviewing laid out by Kvale (1996). He strove to make the atmosphere in the interviews friendly and relaxed, used accessible language, tried to make sure that students understood the questions, making it easier for the students to express themselves freely. Most importantly, the interviewer used different types of questions to test whether he correctly understood what the students tried to express.

The case-to-case generalizability, or transferability as it is often called in qualitative research, should be assessed by the reader of the analysis through careful evaluation of whether the persons, treatments, outcomes, and settings in the paper matches the relevant context for the reader (Lincoln & Guba, 1985). Sample-to-population generalizations are generally not appropriate in qualitative research (Firestone, 1993). *Analytic generalization*, on the other hand, is to generalize particular results to a broader theory (Yin, 1989), e.g. generalizing findings in an interview to theory on how to do strategy interventions. This type of generalization is not dependent on samples and populations (Firestone, 1993). Some of our findings can contribute nuance to theories of how to facilitate students' use of learning strategies.

3.4 Analytical software, interpretation, and overview of methods

All the statistical analyses were conducted in R (R Development Core Team, 2010). The thematic analysis in paper III was conducted in Nvivo (QSR International, 2018). The power analyses in paper I and II were conducted in GPower (Erdfelder et al., 1996).

We discussed Cohen's *d* effect sizes of about 0.20, 0.50, and 0.80 as small, medium, and large, respectively (Cohen, 1988); while Pearsons' correlation coefficiencts of $r < .20$, $r = .20\text{-}.30$, and $r > .30$ were discussed as small, medium, and large (Gignac & Szodorai, 2016; Hemphill, 2003), respectively.

Table 1 – Overview of methods

	Paper I		**Paper II**		**Paper III**
	Phase 1	Phase 2	Study 1	Study 2	NA
Participants					
Study programmes	Energy, Ocean Technology, Physics, Geophysics, Teacher Education, Nanotechnology, Petroleum Technology				
Course	Introductory mechanics				
Sample size	81	≤130	57 (18)	54	12
Design					
RCT	x			x	
Correlational		x	x	x	
Quasi-experimental			x		
Interview					x
Quantitative Analyses					
t-test	x		x	x	
Correlation analysis		x	x	x	
Linear regression		x	x	x	
Logistic regression				x	
Qualitative Analyses					
Quantification of qualitative data			x	x	
Thematic analysis					x
Measures					
Declarative facts test	x	x			
Self-explanation categories			x	x	
Problem-solving test			x	x	
Conceptual test			x	x	
Prior Calculus grade		x			
Final exam score		x			

3.5 Ethical considerations

We tried to adhere to the principles of beneficence, respect, and justice (United States. National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research., 1978) in all our studies. All the studies conducted were reported to and approved by the Norwegian Centre for Research Data (NSD). The students were informed about all the relevant aspects of the studies, see appendix 7.1, before they gave their written consent for participation, see appendix 7.2. Participation was voluntary in every study and the students were informed that they could withdraw their consent at any time. Phase 1 of paper I and study 1 of paper II were anonymous. For the remaining studies, we used an anonymous and self-generated ID-code to connect the different materials. These data were later connected to their final exam and prior calculus grade through the key generated in their written consent forms. We strove to give beneficial treatment to all students in all studies. We also asked research questions whose answers are of minimal risk to the participants but that provide large potential benefits to the participants, future students, lecturers, researchers, and society at large.

4. Results

This section presents the main results and findings from each of the three papers. All results are significant at an alpha level of 5 % unless stated otherwise.

Paper I

In paper I, we found that on average students have a severe lack in their declarative memory for the most basic knowledge in physics, with the control group having an average score of 9/20 on the declarative facts test. We found a very large effect size, Cohen's d = 1.42, of 70 minutes of retrieval practice on the declarative facts test. Further, we found that participation in structured retrieval practice had large correlations with the score on both the declarative facts test, $r = .44$, and the final exam results, $r = .33$. The predictiveness of retrieval practice was further confirmed in a hierarchical regression model with attendance in retrieval practice, prior calculus grade (as a measure of prior ability), and their interaction as predictors of final exam results. Both main effects were significant and, more importantly, the interaction effect was significant, indicating that both attending retrieval practice and being a stronger student predict exam results but that weaker students benefit more from attending lectures with retrieval practice. Finally, we established that knowing basic facts and principles in physics is highly predictive of final exam performance, $r = .62$.

Paper II

In study 1, we found that having engaged in 70 minutes of retrieval practice one week before the tests significantly affected scores on both tests, $d = 0.61$ on the problem-solving test and $d = 0.56$ on the conceptual test. In study 2, we tried to replicate these results with 20 minutes of retrieval practice compared to 20 minutes of self-explaining (work-energy problems), immediately followed by the self-explanation practice for both groups (conservation of mechanical energy and momentum problems) and then the tests. Neither of the effects were significant, $d = 0.4$ for the problem-solving test and $d = -0.2$ for the conceptual posttest. However, we found that retrieval practice changed the quality of the self-explanations and the quality of the problem-solving. The treatment group had significantly more explanations of models that explicated principles and their conditions of application. Although there was no significant difference in the recognition of physics principles during problem-solving, the treatment group more often explicated the conditions of application for the principles, *OR* = 5.76, $p < .001$.

In study 1, we found that self-explanations with principles, with or without explication of the conditions of application, were highly predictive of both problem-solving and conceptual test performance (*r*'s and *β*'s ~ .50). Having engaged in retrieval practice also entered the final hierarchical regression model for conceptual test performance. In study 2, we tried to replicate the results with more participants ($N = 54$ vs. $n = 18$), while also separating the self-explanations into those explanations referring to the physics model and those referring to the mathematical procedures. For score on the problem-solving test, we found a very large correlation with explanations referring to the physics model containing principles and their conditions of application ($r = .50$) and a large correlation for those containing principles but not conditions of application ($r = .30$). We also found a large correlation with explanations referring to the mathematical procedures describing actions and their goals and/or their conditions but without containing reference to principles ($r = .34$). For score on the conceptual test, we found a large correlation with explanations referring to the physics model containing principles but not conditions of application ($r = .39$). Explanations referring to the physics model containing principles and their conditions of application did not reach significance ($r = .25$). The final hierarchical regression model for score on the problem-solving test ($R^2 = .36$) contained model-explanations with principles and their conditions ($\beta = .49$) and procedure-explanations without principles ($\beta = .33$). The final hierarchical regression model for the score on the conceptual test ($R^2 = .22$) contained model-explanations with principles and their conditions ($\beta = .25$) and model-explanations with principles without conditions explicated ($\beta = .40$).

Paper III

In paper III, we found large barriers to students' use of elaborative encoding and self-explanation. Students lacked knowledge of what to do when, why, and how for both strategies. The students ignored the elaborative encoding-questions, but some students apparently did something similar to elaborative encoding during their self-study. Some important barriers to self-explanation were the high perceived cost, low perceived value for easy problems, preferring an intuitive approach, and a pervasive avoidance of the solutions to problems. We also found that, unlike self-explanation during individual study, students liked discussing problem-solutions with peers, a potentially exploitable finding. There was mixed success for retrieval practice in that some students gained knowledge through the practice of what to do when, why, and how for retrieval practice. Some of these students noticed what we expected to be hidden benefits of retrieval practice. Through additional analyses, we found that the problem-solution structure was similar to most of the students' existing problem-solving habits, but the physics model and the strong focus on principles and their conditions of application were new to the students. The biggest barrier to the adoption of physics modeling was some students' practice of "just trying to solve problems". Finally, the Hierarchical Principle Structure for Mechanics was found to seamlessly integrate with students' new and old study habits, being heavily praised and heavily used, especially during problem-solving, and aiding students in getting an overview and seeing the deep structure of the course.

5. Discussion

This section starts with a refresher of how the learning strategies in focus were intended to potentiate each other. Then, I present the results and findings for each of the learning strategies, followed by the solution structure with physics modeling and the Hierarchical Principle Structure for Mechanics. Finally, I present some reflections.

5.1 Intended effects of the learning strategies

Ideally, elaborative encoding helps students acquire the declarative aspect of understanding, i.e. richly interconnected associations within and between physics principles. This should directly improve the success and efficiency of retrieval practice. Ideally, it also improves the students' ability to switch between multiple representations of physics principles, e.g. conceptual, mathematical, and graphical, which helps them self-explain worked examples and to model physical situations. Students would then start the retrieval practice with elaboratively encoded principles, quickly increasing the memory strength of new principles while maintaining and incrementally building the strength of old principles, thereby improving the accessibility of physics principles during self-explanation, problem-solving, and other study tasks. When the elaborative encoding and retrieval practice is centered on a hierarchical principle structure, the students build a hierarchical knowledge structure that helps them understand the structure of the course and improves their working memory performance. Richly connected and strongly encoded principles, together with new knowledge and skills in how to self-explain, help students construct abstract declarative rules when studying worked examples and problem-solutions. Finally, high-quality self-explanations, together with a new awareness of the practice of physics modeling, helps students build correct and useful procedural knowledge and declarative conceptual knowledge, ultimately becoming able to use physics to solve meaningful problems. Although this process is presented sequentially, the students should move back and forth between these methods according to their current needs.

One should also note that this only covers the learning strategies, scaffolding tools, and learning goals focused on in this thesis.

5.2 Elaborative encoding

In the studies of the first two papers, we assumed that students would elaboratively encode the principles without support during the retrieval practice sessions, but it gradually became clear that many did not. Therefore, elaborative encoding was added to the retrieval practice sessions as a response to some students' complaints about lack of understanding and their apparent inability or unwillingness to elaboratively encode new principles without support. We tried integrating elaborative encoding with the retrieval practice sessions through the use of a set of elaborative encoding-questions, designed to prompt a search for meaningful connections within and between new or unstudied principles. Our findings from paper III indicate that this was a failed attempt, as students almost invariably ignored the elaborative encoding-questions.

The conclusion was that elaborative encoding requires further task structure development and instructional resource development to be integrated into physics courses in an effective way. Although this is an area that requires further research (Smith et al., 2010), our main suggestion was to create peer discussion tasks, preferably with mandatory participation, where students present and discuss possible connections within and between principles. This would require instructional resources and associated scaffolds that make it easy to implement and very clear to the students what they are expected to do. Embedding learning strategies in instructional tasks improves students' adoption (Dignath & Veenman, 2020; Hattie et al., 1996; Tricot & Sweller, 2014). Moreover, small-group learning has been shown to correlate with higher achievement (Schneider & Preckel, 2017).

5.3 Retrieval practice of the Hierarchical Principle Structure for Mechanics

The result from paper I was clear in that retrieval practice of the Hierarchical Principle Structure for Mechanics (HPSM) improves students' memory for basic facts and principles. Paper II showed that it changes the quality of self-explanation and problem-solving. When jointly considering the results from paper I and II, it seems likely that retrieval practice of HPSM has either a direct effect on problem-solving performance or an indirect effect through potentiating students' learning from self-explanation, problem-solving, and other study strategies, or both. The findings in paper III also indicate that sustained practice is important for persuading students of the benefits of retrieval practice. Our thematic analysis also indicated that successful implementation of elaborative encoding is crucial for persuading more students and for maximizing the benefits of retrieval practice for everyone. In other words, multiple lines of evidence from paper I, II, and III indicate that retrieval practice of principles from the Hierarchical Principle Structure for Mechanics can have a medium-sized effect on students' problem-solving and, therefore, on exam performance. With effective implementation of elaborative encoding, we may even get large effects.

5.4 Self-explanation

In paper II, we investigated what knowledge representations students should seek to acquire when self-explaining worked examples of physics problems so that we could teach them how to self-explain. We built on this study in paper III by trying to teach the students how to self-explain through integration of self-explanation into the problem-solving seminars. We used a five-step problem-solution structure that clearly distinguished between the physics model and the mathematical procedures to scaffold students' self-explanation efforts. The thematic analysis found substantial barriers to effective implementation of self-explanation. The conclusion was that self-explanation, similarly to elaborative encoding, requires further task structure development and instructional resource development to be integrated into physics courses in an effective way, as students resist using self-explanation for various reasons.

Our main suggestion for improving the implementation of self-explanation was to use the identified facilitating aspect—that students like to discuss solutions with their peers—by embedding self-explanation in a social learning task. Here, we suggested creating conceptual problems that involve explaining physics models and to use the task structure from Peer Instruction (Mazur, 1997) to stimulate thought and discussion. This can be done in classroom lectures as an alternative to the lecturer going through examples on the blackboard.

5.5 The solution structure with emphasis on physics modeling

The findings from paper III indicate that it is relatively easy to persuade some students to start doing physics modeling during problem-solving, merely by exposing them to the solution structure and talking about the concept of modeling the physics in problems. The suggestion was therefore to adopt the practice of uploading solutions to problems that clearly separate the physics model from the mathematical procedures and to clearly name the different structural elements. Lee et al. (2017) showed that students learned more effectively when worked examples (solutions) emphasized the deep structure of the problem rather than the solution procedures.

5.6 The Hierarchical Principle Structure for Mechanics

The Hierarchical Principle Structure for Mechanics was an integral part of all three papers. We found in the thematic analysis in paper III that all the interview participants used it and liked it, that it was especially useful for problem-solving, and that they also used it during other study activities. The idea of a hierarchical principle structure is transferrable to other physics courses, to other STEM courses (Science, Technology, Engineering, and Mathematics), and perhaps even beyond STEM. It may become the most lasting idea from this research project.

5.7 Reflections

Many students are not able to discover effective ways to study physics on their own. Therefore, we need to support students in building effective study habits. However, the thematic analysis in paper III shows that further work is required to give effective support. We need to develop task structures and instructional resources that improve the probability of success and reduce the cost of engaging in the learning strategies.

It seems to be especially difficult to get students to use effective encoding strategies, such as elaborative encoding and self-explanation. As discussed in section 2.1, we can directly encode concrete knowledge from our senses, i.e. passively, or we can construct abstract knowledge with our minds, i.e. actively. Passive learning feels much easier and, therefore, students may actually believe that they learn more effectively from lectures and reading than more active methods like elaborative encoding and self-explanation (Bjork et al., 2013; Kirk-Johnson et al., 2019), which may be correct for concrete knowledge but not for abstract knowledge. Retrieval practice is not an encoding strategy, as students are meant to retrieve already encoded chunks. This may be part of the reason why we had more success with getting students to engage with retrieval practice. However, based on the thematic analysis in paper III, those students who resisted retrieval practice also seemed to lack meaningful encoding of the principles. Therefore, retrieval practice also became a matter of encoding the principles for these students. Hence, it seems that there is a general tendency for students to resist doing active manipulation of declarative knowledge to create new declarative knowledge, potentially because of the high mental effort required or because it is difficult to learn how to do it. This may mean that students require more support to adopt and effectively use active encoding strategies.

Our main suggestion for improving the implementation of these encoding strategies was to leverage social learning processes, which students in paper III indicated were less effortful than individual learning. A fruitful path may be to combine cognitive and social perspectives on learning, for example by using theory on how to improve discussions to increase the time students spend engaged in effective cognitive processes. If we use carefully designed task structures and instructional resources together with insights from sociocultural research on how to facilitate fruitful group dynamics, more students may adopt these effortful learning strategies.

Finally, we also want to integrate these learning strategies in a way that meshes with the students' other study habits. As mentioned, there is still a role for passive learning through reading and lectures because students must passively encode some information before they can actively manipulate that information, creating abstract knowledge from concrete knowledge. However, proper elaborative encoding-resources can help guide the students' attention towards the most important information and stimulate more active learning during reading and lectures. This may also be combined with other established strategies for active learning during reading and lectures. We also want students to bring retrieval practice into their problem-solving, by actively trying to retrieve the principles they need. Existing instructional techniques with active learning, such as Peer Instruction, give students valuable practice in modeling situations with physics principles when properly implemented, also exposing them to, and challenging them on, common misconceptions. Making students aware of all these connections is a challenging task, one which we need to tackle to reach the potential of physics education.

6. Conclusions

This section presents practical implications for physics education, discusses the strengths and limitations of the project, and suggests further research.

6.1 Practical implications for physics instruction

Physics instructors can strive to support the construction of each aspect of the cognitive knowledge structure for principles: Associative links within and between physics principles, strong memories of principles, hierarchical structuring of the memories, abstract declarative rules of problem-solutions, and knowledge and skills for physics modeling. This is, of course, not an exhaustive list of relevant knowledge of principles, but it captures many of the most important aspects.

We did not succeed in finding an effective way to support the construction of associative links within and between principles. Our general suggestion is to support student discussions of important relationships within and between principles.

To support memory strength and hierarchical structuring of memories, the structured retrieval practice of the Hierarchical Principle Structure for Mechanics can easily be transferred to other introductory mechanics courses. One may have to remove the parts that are irrelevant to the specific course, e.g. removing fluid mechanics. The easiest way to adapt the idea to other physics courses is to create tables of important principles. One may also create new hierarchical principle structures for other courses and physics domains.

To support students' construction of abstract declarative rules of problem-solutions, one can make sure to explicate all the important elements of high-quality explanations—action-descriptions, principles, conditions, and goals—when explaining examples to students, also emphasizing the difference between the physics model and the mathematical procedures. We apparently did not succeed in finding an effective way to teach many students high-quality self-explaining.

To improve students' knowledge of and skills in physics modeling, one can use the problem-solution structure when solving problems on the blackboard and when uploading solutions.

6.2 Practical implications for instruction in other domains

The cognitive knowledge structure for physics principles is probably very similar to the cognitive knowledge structure for principles in other scientific domains. Mathematicians, chemists, biologists all use domain principles to create conceptual models to describe and solve problems. They learn from abstracting the underlying rules in solutions. They are well-served by having a hierarchical structuring of the domain principles. They need strong memories and they need meaningful associative links within and between the domain principles. Therefore, they are probably also well-served by effective elaborative encoding, structured retrieval practice, hierarchical principle structures, high-quality self-explaining, and a strong focus on modeling with domain principles.

One can also see similarities to my Ph.D. Although a Ph.D. has a more exploratory character than introductory physics courses and the problems are more ill-structured, I still relied on the same learning and performance processes as physics students and I deliberately used the same learning strategies that I have taught. I have spent countless hours—on buses, in the shower, in bed—thinking about connections between known principles of learning, spontaneously or deliberately encoding them elaboratively. I have used retrieval practice to strengthen my memories of the mathematical equations of learning and performance from the ACT-R theory. I have drawn tens or even hundreds of diagrams, hypothesizing about the hierarchical structure of connections between different learning principles, concepts, and theories. I have tried to abstract the rules underlying what has worked or not worked in other researchers' and instructors' experiments and instructional methods. And I have used learning principles to create conceptual models of instructions, trying to solve the problem that many students fail physics courses or fail to acquire the conceptual knowledge required to solve complex problems.

6.3 Strengths

The use of mixed methods, investigating both effects and processes, is a strength of the research project (Johnson et al., 2007; Johnson & Onwuegbuzie, 2004). The correlations and effect sizes in paper I and II were generally large and for meaningful outcomes, meaning that they were educationally relevant and not just of theoretical interest (Hattie, 2009). The interventions were evidently done with ecologically valid units, treatments, outcomes, and settings (Shadish et al., 2001) so the results should be widely generalizable. Finally, some of our instructional interventions are easily implementable by other researchers and instructors.

6.4 Limitations

The students ignored our self-developed elaborative encoding-questions, so there are still many open questions regarding the implementation and efficacy of elaborative encoding of physics principles.

In phase 2 of paper I, we relied on correlational data to investigate the effects of retrieval practice on final exam scores. However, the conclusion was supported by the quasi-experimental effects of retrieval practice on problem-solving in study 1 of paper II. Further, although the effect on problem-solving was not statistically significant for the experimental test in study 2, the effect was of educationally relevant size (Hattie, 2009). Moreover, this study was underpowered, had high variance on the problem-solving test, involved a lower treatment level than in study 1, and the control was conservative since the control task may have transferred to the test.

The two studies on self-explanation in paper II were underpowered for exploring more nuances in the effects of different categories of self-explanations. We also relied on correlational data. Finally, although improbable, results for written self-explanations may not transfer to spoken or thought self-explanations.

6.5 Future research

Further research needs to be done on how to facilitate students' use of elaborative encoding, by developing an effective task structure with associated instructional resources. The cognitive and social processes during the elaborative encoding task should be investigated, for example through analyzing group discussions and interviews. Eventually, the interaction effect between effective implementation of elaborative encoding with structured retrieval practice should be investigated for factual knowledge, conceptual knowledge, and exam score.

Further research needs to be done on retrieval practice to investigate the effects of different treatment levels of retrieval practice in an RCT. As mentioned, the interaction effect between elaborative encoding and retrieval practice should also be investigated. Finally, the students' mental processes during retrieval practice should be investigated by means of think-aloud protocols.

Further research needs to be done on self-explanation to develop an effective task structure with associated instructional resources for improving students' self-explanations. The cognitive and social processes during the self-explanation task should be investigated, for example through analyzing group discussions.

Further research needs to be done on the Hierarchical Principle Structure for Mechanics, for example by experimentally testing the effects of having a hierarchical principle structure available during study and testing. Research should also be expanded to retrieval practice of principle structures in other physics courses.

Further research needs to be done on teacher professional development for the implementation of the learning strategies in physics classrooms.

Finally, getting students to use effective learning strategies is a complex problem, which requires that we draw upon other fields and theories than just cognitive science, educational psychology, and physics education research. In the future, we also need to look further into our students' motivation, cultural background, personality, beliefs about learning and science, and the social aspects of their learning.

7. Appendices

7.1 Letter with information about project

Forespørsel om deltakelse i forskningsprosjektet

"Bruk og bevisstgjøring av læringsstrategier i introduksjonsfag i fysikk"
&
"Establishing Standard practices in STEM education at UiB"

Bakgrunn og formål
Formålet med studien er å optimere bruk av læringsstrategier for læring av fysikk. Opplegget for forelesningene er designet med grunnlag i teori og forskning på instruksjonsmetoder og læringsstrategier.

Studien er en del av doktorgradsprosjektet til Vegard Gjerde innen fysikkdidaktikk.

Du blir spurt om å delta fordi du tar PHYS111 – Mekanikk 1 dette semesteret.

Vegard Gjerde samarbeider også med Assoc. Prof. Sehoya Cotner fra University of Minnesota. Hun forsker på hvordan noen psykologiske variabler påvirker eksamensresultater. Noen av svarene fra spørreskjemaene, samt eksamensresultater som er samlet inn basert på samtykke, vil deles med Assoc. Prof. Cotner etter endt semester. Disse dataene vil være fullstendig anonyme.

Hva innebærer deltakelse i studien?
Det vil bli regelmessige treningsopplegg i forelesningene med påfølgende tester, der en selv kan velge om materialet blir gjort tilgjengelig for forskning. Forelesningsopplegget vil være det samme for alle uavhengig av hvorvidt en velger å tilgjengeliggjøre sitt arbeid for forskning. Å delta i studien innebærer at du fyller ut en personlig kode ved skriftlig arbeid i forelesninger. Det vil også være to innsamlinger av spørreskjema for de som velger å delta. Studentnummer og samtykke vil samles inn for å innhente eksamensresultater som kan kobles til skriftlig arbeid. Samtykke vil samles inn i forelesning.

Det vil være trekning av flere gavekort på grunnlag av deltakelse i datainnsamlinger i forelesninger. For å delta på trekninger av ByGavekort som finner sted ved semesterslutt, må samtykke gis for innhenting av eksamensinformasjon. De som samtykker og oppgir studentnummer vil også automatisk være med i trekning av to ByGavekort på 2000kr. Totalt vil det trekkes opp mot 30000kr i ByGavekort basert på deltakelse i forskjellige innsamlinger. Mer informasjon om trekninger gis i forelesning, på MittUiB, og ved hver enkelt datainnsamling.

Det er frivillig å delta
Det er frivillig å delta i prosjektet. Hvis du velger å delta, kan du når som helst trekke samtykke tilbake uten å oppgi noen grunn. Alle opplysninger om deg vil da bli anonymisert.

Ditt personvern – hvordan vi oppbevarer og bruker dine opplysninger
Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet. Vi behandler opplysningene konfidensielt og i samsvar med personvernregelverket.

- Det er bare prosjektleder som vil ha tilgang til personopplysninger som kan kobles til innsamlet data. Dette lagres passordbeskyttet på universitetets server. Når resultater er ferdig innhentet vil alle dataene anonymiseres.

Figure 2 – Letter with information about the research project, sent January 2020. The letter sent in 2019 was highly similar. (page 1)

- Deltakerne vil ikke kunne gjenkjennes i eventuelle publikasjoner.
- Dataene vil inngå i statistiske modeller i publikasjoner.

Hva skjer med opplysningene dine når vi avslutter forskningsprosjektet?
Prosjektet skal etter planen avsluttes 31.12.2024. Senest da vil alle opplysningene bli anonymisert.

Dine rettigheter
Så lenge du kan identifiseres i datamaterialet, har du rett til:
- innsyn i hvilke personopplysninger som er registrert om deg,
- å få rettet personopplysninger om deg,
- få slettet personopplysninger om deg,
- få utlevert en kopi av dine personopplysninger (dataportabilitet), og
- å sende klage til personvernombudet eller Datatilsynet om behandlingen av dine personopplysninger.

Hva gir oss rett til å behandle personopplysninger om deg?
Vi behandler opplysninger om deg basert på ditt samtykke.

På oppdrag fra Universitetet i Bergen har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

Hvor kan jeg finne ut mer?
Hvis du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med:
- Universitetet i Bergen ved Vegard Gjerde.
- Vårt personvernombud: Janecke Helene Veim
- NSD – Norsk senter for forskningsdata AS, på epost (personvernombudet@nsd.no) eller telefon: 55 58 21 17.

Samtykke til deltakelse i studien

Samtykke til deltakelse av studien innhentes ved datainnsamling.

Figure 3 – Letter with information about the research project, sent January 2020. The letter sent in 2019 was highly similar. (page 2)

7.2 Informed consent forms

Samtykke til innhenting av eksamenskarakterer

Dette prosjektet er utviklet for å evaluere bruk av læringsstrategier i fysikk. Kunnskap om dette kan bidra til kvalitetsutvikling av studieopplegg.

Du blir bedt om å fylle ut ditt studentnummer. Dette er nødvendig for å knytte informasjon fra studien opp mot eksamensresultater. Dersom du ikke har studentnummeret tilgjengelig i denne omgang vil du kunne oppgi det ved en senere anledning, slik at det kan kobles til din personlige kode. Hvis du ikke ønsker å oppgi studentnummer og samtykke kan du fortsatt være med på lotteritrekninger som skjer i forelesninger, men ikke de som skjer ved slutten av semesteret. Ved å samtykke til innhenting av eksamensinformasjon og poengsum ved inntak er du også automatisk med i trekning av to ByGavekort på 2000 kr. Lever til Vegard Gjerde ved en senere anledning om du ikke husker studentnummeret ditt.

Informasjonen vil oppbevares og behandles i henhold til personopplysningsloven med forskrifter. Prosjektet er godkjent av Norsk Senter for Forskningsdata. Alle data vil bli anonymisert så snart de aktuelle opplysningene er tilgjengelige. Data vil bli behandlet konfidensielt av prosjektleder. Deltakelse er frivillig, men ditt bidrag av stor betydning. På forhånd takk for at du deltar!

Vegard Gjerde samarbeider med Assoc. Prof. Sehoya Cotner fra University of Minnesota. Hun forsker på hvordan noen psykologiske variabler påvirker eksamen. Hvis du også deltar på spørreskjemaene, vil noen av svarene samt eksamensresultatet deles med Assoc. Prof. Cotner etter endt semester. Disse dataene vil være fullstendig anonyme.

Vennlig hilsen
Vegard Gjerde, prosjektleder

Jeg har mottatt og forstått informasjon om prosjektet *Bruk og bevisstgjøring av læringsstrategier i introduksjonsfag i fysikk*, og har fått anledning til å stille spørsmål (**kryss av for ja**). ☐

Under kan du skrive inn din personlige kode for kobling av forskjellige data. Det er viktig at du skriver samme koden hver gang. Koden skal bestå av første bokstav i din fars fornavn, første bokstav i din mors fornavn, datoen du er født, og måneden du er født, e.g. <Ola, Kari, 5. mars> blir <OK0503>.:

Personlig kode: F M d d m m

Jeg samtykker til innhenting av eksamensdata og poengsum ved inntak, og trekning av gavekort ved å skrive studentnummer. Personlig kode må også utfylles.
Studentnummer: ☐☐☐☐☐☐

Figure 4 – Informed consent form for collection of exam results in the study of 2020. The consent form was highly similar in 2019 were highly similar.

7.3 Three versions of the Problem-Solving Process (PSP)

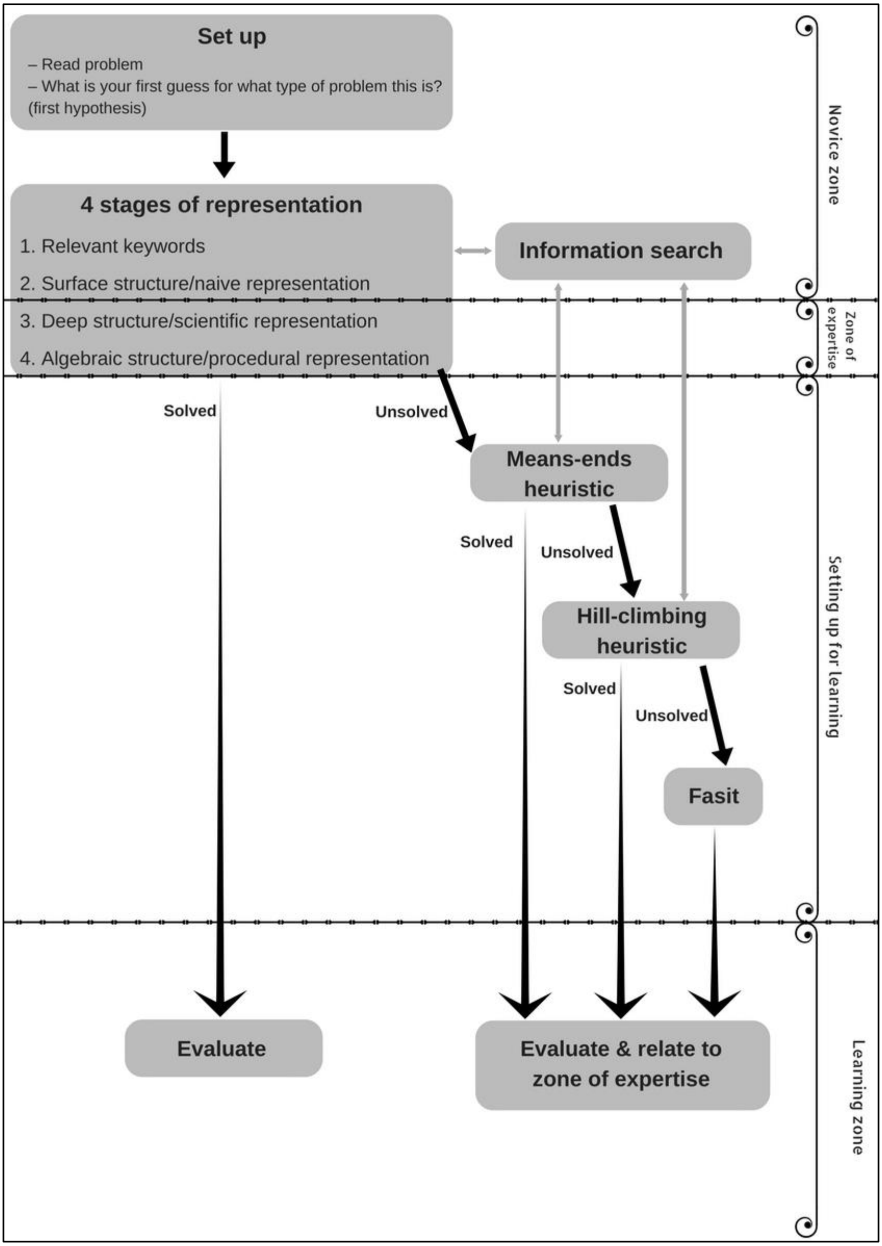


Figure 5 - The first version of the Problem-Solving Process (Oppgavehjelpen). This version was never used in an intervention.

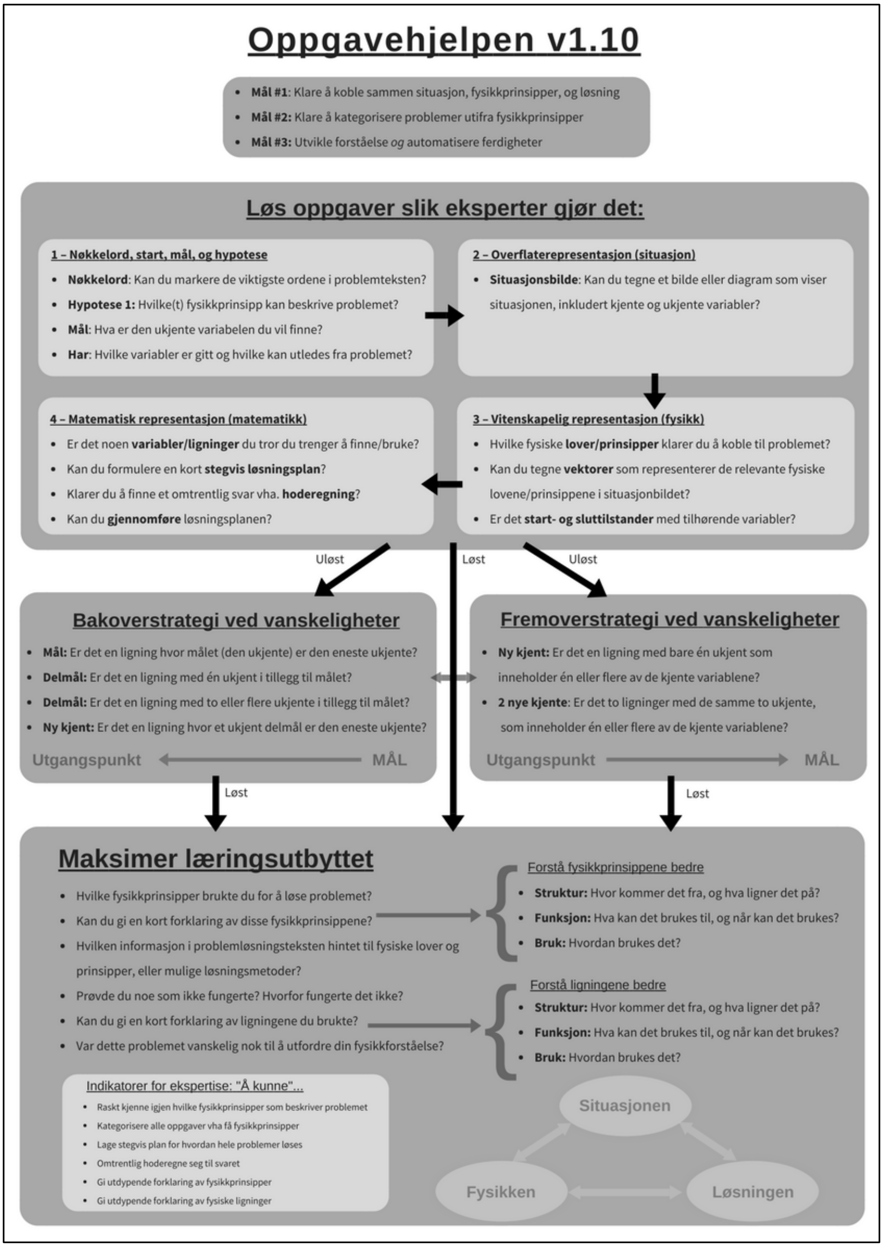


Figure 6 - The version of the Problem-Solving Process (Oppgavehjelpen) used in the unpublished intervention study.

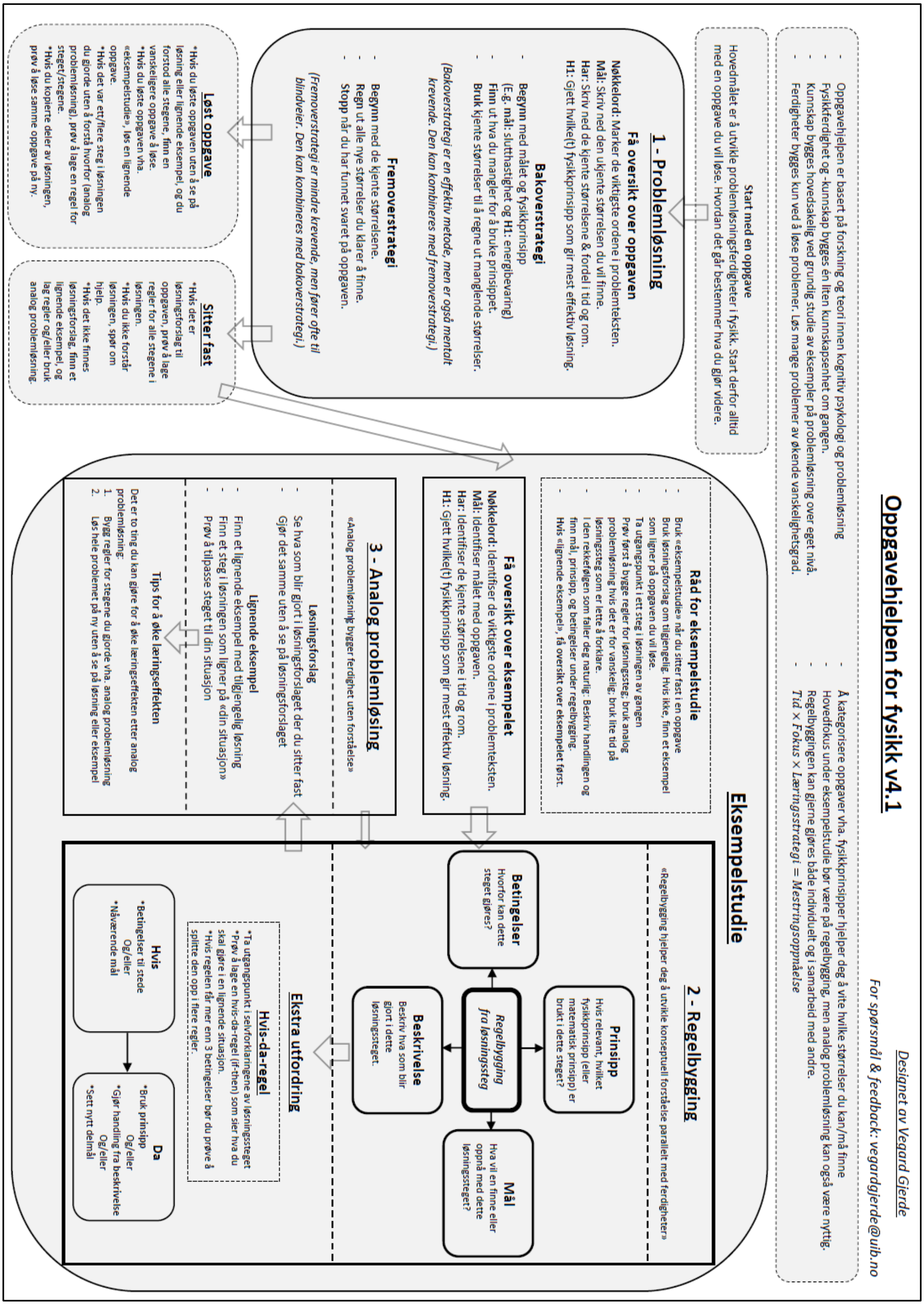


Figure 7 - The last version of the Problem-Solving Process (Oppgavehjelpen). No English version was made. This version was never used in an intervention.

7.4 The Hierarchical Principle Structure for Mechanics

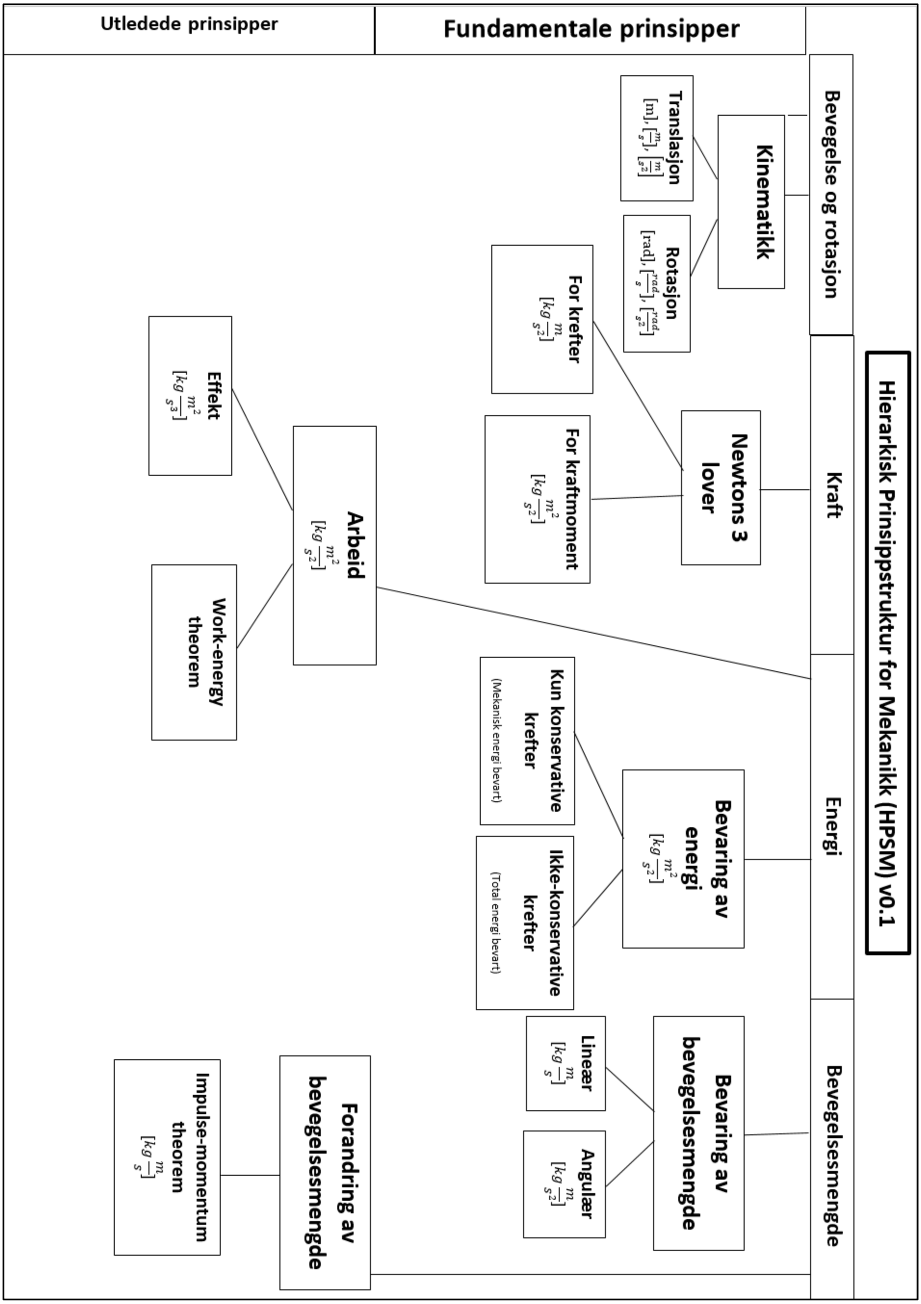


Figure 8 – The first version of the Hierarchical Principle Structure for Mechanics. No English version was made. This version was never used in an intervention.

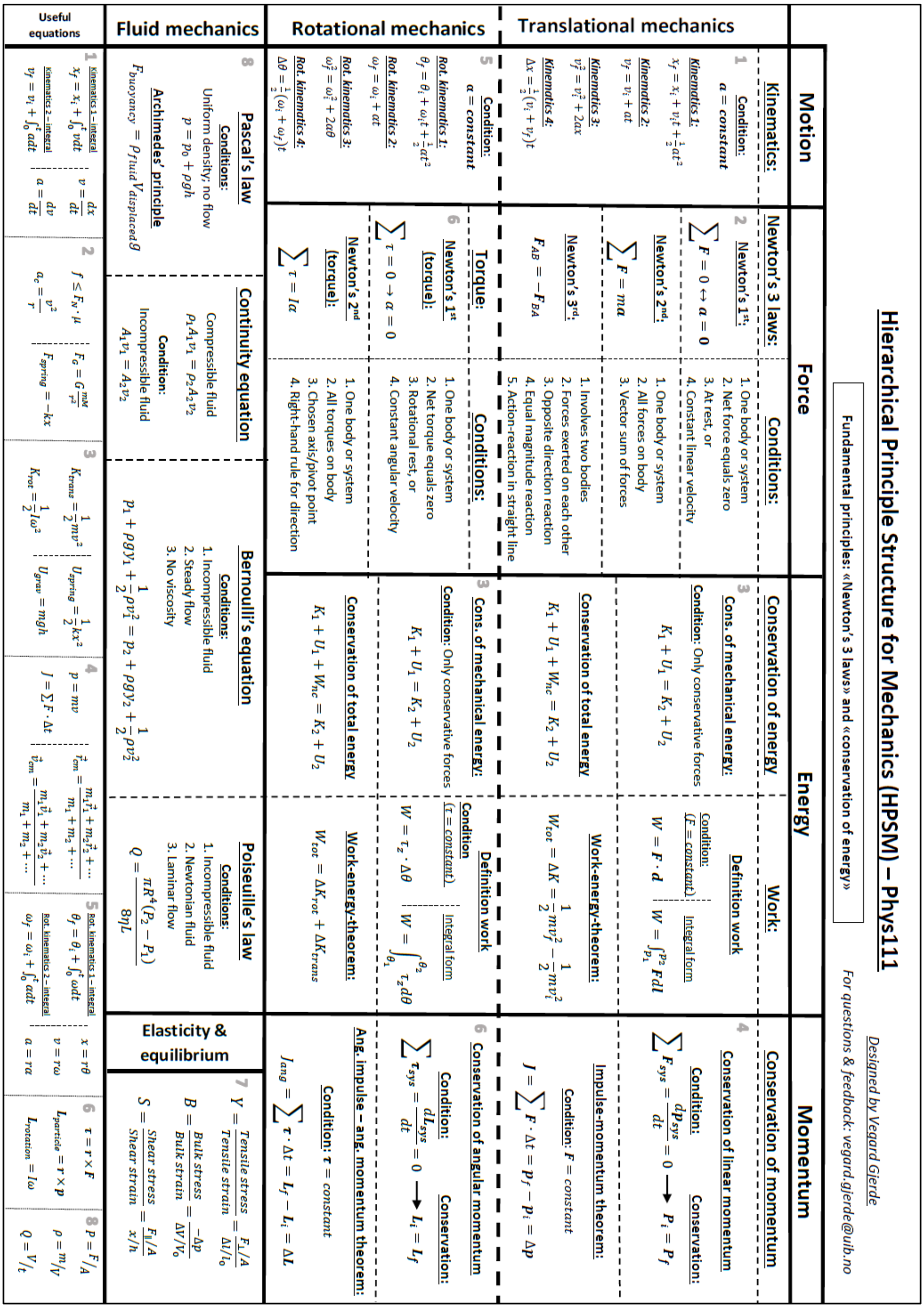


Figure 9 – The last version of the Hierarchical Principle Structure for Mechanics, front side.

Symbol	Name	SI Units
t:	Time	s
x:	Distance	m
v:	Velocity/speed	m/s
a:	Acceleration	m/s^2
F:	Force	$N = Newton = kg\, m/s^2$
k:	Spring constant	N/m
$\boldsymbol{\mu}$:	Coefficient of friction	NA
f:	Frictional force	N
$\boldsymbol{a_c}$:	Centripetal acceleration	m/s^2
$\boldsymbol{G}$:	Gravitational constant	$6.67 * 10^{-11}\, m^3 kg^{-1} s^{-2}$
K:	Kinetic energy	$J = Joule = kg\, m^2/s^2$
U:	Potential energy	J
W:	Work	J
$\boldsymbol{W_{nc}}$:	Work by non-conservative forces	J
d:	Distance	m
P:	Total linear momentum	$kg\, m/s$
p:	Momentum of object	$kg\, m/s$
J:	Impulse	$kg\, m/s$
$\boldsymbol{\theta}$:	Angle/Angular displacement	rad
$\boldsymbol{\omega}$:	Angular speed/frequency	rad/s
$\boldsymbol{\alpha}$:	Angular acceleration	rad/s^2
$\boldsymbol{\tau}$:	Torque	$kg\, m^2/s^2$
I:	Moment of inertia	$kg * m^2$
L:	Angular momentum	$kg\, m^2/s$
ρ:	Density	$kg * m^{-3}$
p:	Pressure	$Pa = Pascal$
η:	Viscosity	$Pa * s$
Y:	Young's modulus	Pa
B:	Bulk modulus	Pa
S:	Shear modulus	Pa

Spørsmål for Elaborative Encoding (EE)

Tenk på og diskuter disse spørsmålene for å utvikle forståelsen av hvert prinsipp og definisjon i HPSM.

For hvert prinsipp (og definisjon):

Detaljnivå

1. Hvilke begrep og SI-enheter tilhører symbolene i prinsippet?
2. Hva betyr disse begrepene for deg? (nye begreper)

Prinsippnivå

3. Hva heter prinsippet? Har du tanker om hvorfor?
4. Hva er betingelsen(e) for prinsippet?
5. Hvorfor er det en betingelse for det prinsippet?
6. Hva skjer hvis én variabel i prinsippet endrer størrelse?

Hierarkinivå

7. Hva er navnet på rekken (og kolonnen) det er plassert i?
8. Hvilke likheter og ulikheter ser du med andre prinsipper i HPSM?
9. Er det empirisk eller kan det utledes fra andre prinsipper i HPSM? Hvordan?

Figure 10 – The last version of the Hierarchical Principle Structure for Mechanics, back side. Elaborative encoding-questions in Norwegian.

7.5 Retrieval sheet example

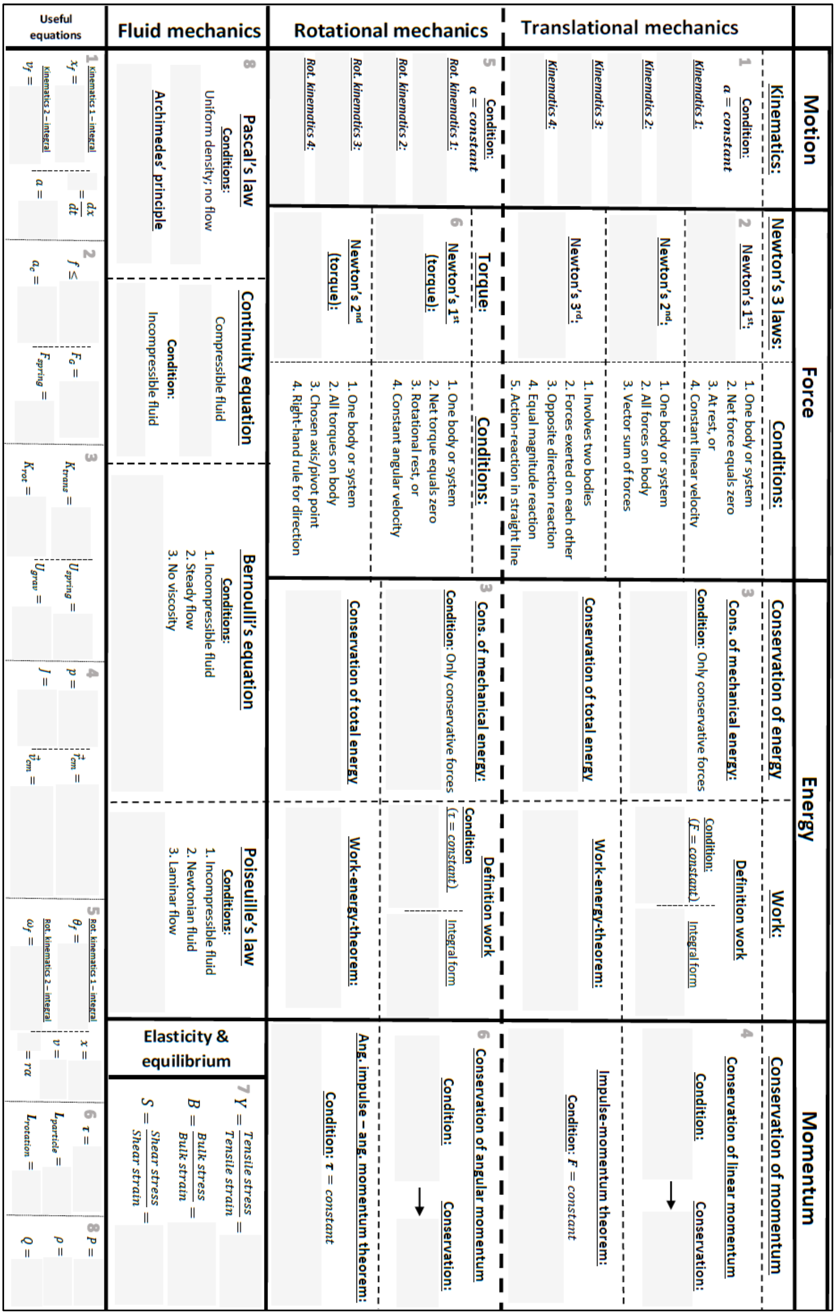


Figure 11 – The retrieval sheets used in the spring of 2020.

7.6 Retrieval practice-advice

Table 2 - Retrieval practice-advice as presented on a projector screen during the retrieval practice sessions. The elaborative encoding-questions were shown adjacently.

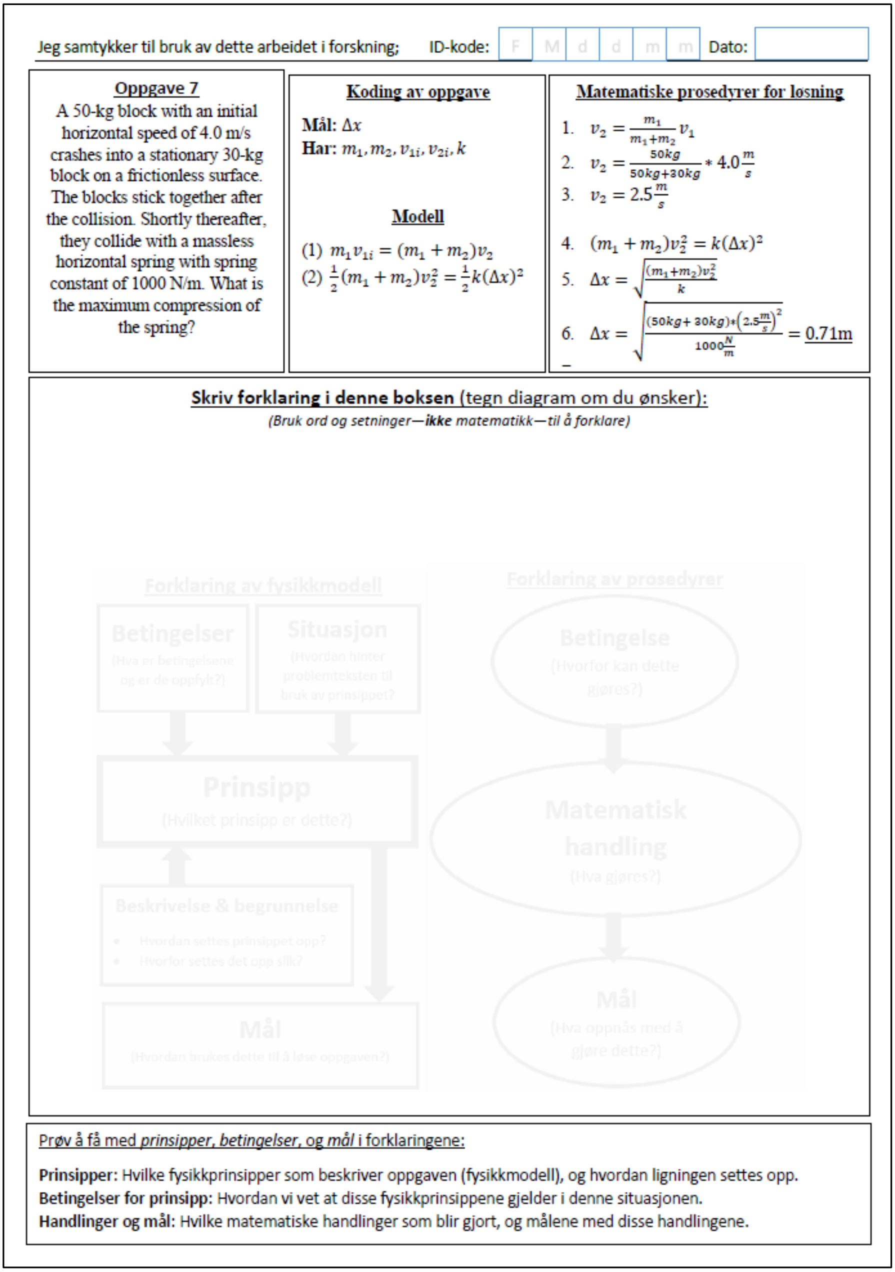
Advice for Retrieval Practice *(Purpose: Maximize memory strength)*
1. First, fill in as much as you can remember. (If you have remembered a whole box in HPSM at least four sessions in a row and you feel it sticks, you can skip it this session and rather put a checkmark in that box) 2. Retrieval is most effective when the retrieval attempt is successful; restudy is most effective after retrieval failure. 3. When you go 15-30 seconds without remembering more: a. Restudy and retrieve old memories mentally b. Write down the mentally retrieved memories c. Repeat step a & b until all the old memories are retrieved 4. Use elaborative encoding on one new HPSM-box at the time, and: a. Write down what you remember b. Do mental retrieval plus feedback on the rest until they stick c. Write down what you did not remember in step a 5. Make time for retrieval repetition of new memories on the backside [of the retrieval sheets]

7.7 Elaborative Encoding-Questions

Table 3 - Elaborative encoding-questions, also be seen in Norwegian on the back of HPSM. During the retrieval sessions, the bolded questions were visible on a projector screen adjacent to the retrieval practice-advice.

Questions for Elaborative Encoding
<u>Detail-level</u> 1. **What concepts and SI-units belong to the symbols in the principle?** 2. What do these concepts mean to you? **<u>Principle-level</u>** 3. **What is the principle called? Any thoughts on why?** 4. **What are the conditions of application for the principle?** 5. Why is that a condition for the principle? 6. **What happens if one variable in the principle changes size?** **<u>Hierarchy-level</u>** 7. **What is the row name and column name it is placed in?** 8. **What similarities and dissimilarities do you see with other principles in HPSM?** 9. Is it empirically derived or is it deductively derived from other principles in HPSM?

7.8 Self-explanation worksheet example



Jeg samtykker til bruk av dette arbeidet i forskning; ID-kode: F M d d m m Dato:

Oppgave 7

A 50-kg block with an initial horizontal speed of 4.0 m/s crashes into a stationary 30-kg block on a frictionless surface. The blocks stick together after the collision. Shortly thereafter, they collide with a massless horizontal spring with spring constant of 1000 N/m. What is the maximum compression of the spring?

Koding av oppgave

Mål: Δx

Har: $m_1, m_2, v_{1i}, v_{2i}, k$

Modell

(1) $m_1 v_{1i} = (m_1 + m_2) v_2$

(2) $\frac{1}{2}(m_1 + m_2) v_2^2 = \frac{1}{2} k (\Delta x)^2$

Matematiske prosedyrer for løsning

1. $v_2 = \frac{m_1}{m_1 + m_2} v_1$
2. $v_2 = \frac{50kg}{50kg + 30kg} * 4.0 \frac{m}{s}$
3. $v_2 = 2.5 \frac{m}{s}$
4. $(m_1 + m_2) v_2^2 = k (\Delta x)^2$
5. $\Delta x = \sqrt{\frac{(m_1 + m_2) v_2^2}{k}}$
6. $\Delta x = \sqrt{\frac{(50kg + 30kg) * (2.5 \frac{m}{s})^2}{1000 \frac{N}{m}}} = 0.71m$

Skriv forklaring i denne boksen (tegn diagram om du ønsker):

*(Bruk ord og setninger—**ikke** matematikk—til å forklare)*

Prøv å få med *prinsipper, betingelser*, og *mål* i forklaringene:

Prinsipper: Hvilke fysikkprinsipper som beskriver oppgaven (fysikkmodell), og hvordan ligningen settes opp.
Betingelser for prinsipp: Hvordan vi vet at disse fysikkprinsippene gjelder i denne situasjonen.
Handlinger og mål: Hvilke matematiske handlinger som blir gjort, og målene med disse handlingene.

Figure 12 – Worksheet for written self-explanations during the problem-solving seminars in the spring of 2020. The self-explanation worksheet in paper II contained similarly structured tasks. The dim figures were scaffolding flow-charts for formulating self-explanations.

7.9 Interview guide from paper III

We have omitted some questions that were only related to digital teaching after the Covid-19 shutdown.

Starting the interview

- Interviewer introducing himself
- Turning on presentation slides with contextual material, see Table IV – The content of the slides for contextualizing the questions
- Asking for permission to turn on the camera
- Starting:

Table IV – The content of the slides for contextualizing the questions

- **Part 1 – Lectures**
  - Slide from traditional lecture
  - Peer Instruction conceptual problem
- **Part 2 – Problem-solving and self-explanation**
  - Slide of problem-solution from the problem-solving seminar
  - Written self-explanation worksheet
  - Problem sheet for problem-solving seminars
  - A solution from the problem-solving seminar (using the solution structure)
- **Part 3 – HPSM, retrieval practice, and elaborative encoding**
  - The Hierarchical Principle Structure for Mechanics
  - Retrieval practice sheets
  - Retrieval practice advice
  - Elaborative encoding-questions
  - Sample elaborative encoding answers
  - Announcement advising use of elaborative encoding

Part 1 – Lectures

1. How often did you attend lectures before the Covid-19 shutdown?
   a. What are your reasons for attending lectures?
   b. What did you do in the lectures to maximize your learning?
      i. Probing questions on how, if needed
2. To what extent did you attend the peer instruction sessions before the Covid-19 shutdown?
   a. What did you do during the different phases of peer instruction?

i. Probing questions on how, why, and reflections on benefits and drawbacks

<u>Part 2 – Problem-solving and self-explanation</u>

3. Do you solve many problems when you study for the exam in this course?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
4. What would you say is your approach when you try to solve problems in this course?
    a. Probing questions on how/problem-solving strategies and repairing strategies when stuck
5. [The seminar leader] used a certain structure for solving problems, with coding, diagrams, physics model, and procedures in the problem-solving seminars: Do you try to do something similar when you solve problems?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
        i. Why (not)?
6. Have you attended the problem-solving seminars?
    a. Why do you choose to (not) attend the problem-solving seminars?
    b. How do you use the problem-solving seminars?
        i. Probing questions on how, why, and reflections on benefits and drawbacks
7. Three weekly self-explanation problems have been uploaded each week. To what extent have you used these?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
8. [The seminar leader] has also tried to teach the students how to self-explain worked examples to maximize learning, by focusing on the principles, conditions, and how to set up the physics model, and the goals of the mathematical procedures: Do you try to explain to yourself in this way when you study solutions?
    a. Probing questions on how, why, and reflections on benefits and drawbacks

<u>Part 3 – HPSM, retrieval practice, and elaborative encoding</u>

9. What do you call this sheet? *[shows slide with the Hierarchical Principle Structure for Mechanics]*
10. To what extent have you used the 'hierarchical principle structure'/'formula sheet'/'principle structure' in your study?

   a. Probing questions on how, why, and reflections on benefits and drawbacks
11. To what extent have you attended the retrieval practice sessions in the lectures before the Covid-19 shutdown?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
12. [The first author] had some advice for how to do retrieval practice. Did you follow this advice during the retrieval practice sessions?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
13. [The first author] has recommended that students try to answer the elaborative encoding-questions during self-study, alone or in groups. Have you ever done that?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
    b. He also uploaded examples of how to answer these elaborative encoding-questions. Have you noticed or used this?

Ending the interview

Source of data

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Scientific papers

Paper 1

Retrieval practice of a hierarchical principle structure in university introductory physics: Making stronger students

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(Received 22 November 2019; accepted 10 March 2020; published 21 April 2020)

Introductory physics is taught to several hundred thousand university students every year. It is seen as especially difficult by many and the failure rate is often high. A relevant question is whether one can increase the success rate among the weaker students? Retrieval practice is an established learning strategy with large benefits. However, as pointed out last year in this journal, hardly any systematic research has been done on retrieval practice in physics. Here we present a novel tool for retrieval practice in physics called the hierarchical principle structure for mechanics (HPSM). HPSM hierarchically organizes the essential principles, equations, and definitions for translational, rotational, and fluid mechanics, to emphasize meaningful connections. We investigated HPSM in a two-phase study. First, we present a randomized controlled experiment showing that 70 min of retrieval practice of HPSM had a very large effect on a declarative factual test compared to 70 min of problem study, $d = 1.42$. In the second phase, which was carried out the following year, we implemented distributed retrieval practice of HPSM in the first 15 min of 16 lectures. Although difficult to disentangle the effect from the lectures it was embedded in, distributed retrieval practice of HPSM seems to promote factual knowledge ($r = 0.44$) and better exam results for the weaker students (significant main and interaction effects).

DOI: 10.1103/PhysRevPhysEducRes.16.013103

I. INTRODUCTION

Some learning strategies are more effective than others [1], and retrieval practice is one of the learning strategies with the most positive evidence [1–11]. The effects from retrieval practice are so robust across different contexts, both in labs and in applied settings, that many cognitive scientists recommends its use for education [8,12]. However, there is still a need for more research on retrieval practice in educational settings [1,12], and especially in physics education where it has hardly been studied at all as pointed out in a recent publication in this journal [11]. Research in education, including physics education, still focuses more on encoding processes than on retrieval [13]. There seems to be an underlying fear that students will acquire disconnected facts, and ultimately have lower understanding [14]. Even Dunlosky *et al.*, who strongly encourage efforts to improve memory for facts, supply caveats against "robotically memorizing facts" [1]. In a rare case of research on retrieval practice in physics, an advantage was found for retrieval practice over peer discussion of conceptual instruction [11]. In this study, the students watched a video lecture about speed and energy conservation, and then did either retrieval-based or peer discussion-based restudy of the content in the lecture. In a more recent study, Gjerde *et al.* found positive effects on problem solving performance from having engaged in retrieval practice of physics principles [15]. We did not find any published systematic study of retrieval practice for memorizing essential principles and definitions in physics, even though presumably this is more effective than having no specific method.

The probability of being able to remember a fact is dependent on the activation of the fact. Activation is an additive function of the base strength of the memory and associative activation from contextual cues [16,17]. When first encoded, a new fact has low base strength and few associative ties to contextual cues. The act of retrieving a memory increases the base strength of the memory [18,19]. This memory strength is a function of the recency and frequency of practice, and reflects past usefulness [16,20]; the more a fact is retrieved, the more likely it will be useful in the future. The increased strength of memories due to retrieval practice may make memories less context dependent for future recall, promote insight, inference, and generalization [21], and may enable students to use the practiced information more flexibly when meeting new concepts thereby potentiating further learning [5,22,23]. In support of these claims, retrieval practice seems to be better than restudy for tests of transfer of knowledge [4,22,24,25].

Further, the base strength of memory chunks seems to directly influence learning and working memory capacity [26,27]. There may also be individual differences corresponding to working memory capacity in the maximum amount of associative activation from contextual cues, making base strength especially important for students with a smaller working memory and when complexity increases [26–29].

Students will ultimately be tested on their ability to solve problems, not their memory of physics principles and definitions. However, declarative memory is essential as problem solving requires a lot of retrieval of physics principles, definitions, and solution strategies, especially during the planning phase [30]. Performance tends to deteriorate when a problem-solving task becomes more complex and most of the errors and failures seem to be due to misretrievals [31]. Hence, poor memory strength may be disguised as poor problem-solving skills, with resulting calls for ever more problem solving. The cost of failure is also high when solving problems [32], in large part because of lost time spent floundering.

Do students really lack knowledge of physics principles and definitions? And is it not better to just learn them through regular study? The results from phase 1 of the study, reported here, show that many students have severe lacks in knowledge of the most basic physics definitions and principles. As a student in one of our tests remarked: "I do not walk around remembering equations six weeks before the exam," unknowingly referring to Newton's second law. Some students do learn physics definitions and principles by retrieving during individual problem solving, as some students reported in our surveys. However, most novices, and especially the weaker students, tend to search for specific equations in textbooks or cramming sheets while solving problems [33–35]. Retrieval practice has the potential to narrow the gap between stronger and weaker students by making principles and their conditions of application more accessible and recognizable to weaker students. Gjerde *et al.* [15] found that retrieval practice of physics principles and their conditions significantly increased the probability that students mentioned conditions of application of principles while solving physics problems (odds ratio $= 5.76$).

In this paper we present a novel tool descriptively called the hierarchical principle structure for mechanics (HPSM) (see Supplemental Material [36] for the current version). HPSM contains the most relevant principles and definitions for an introductory mechanics course at a large university in Norway and was designed by the first author. It is hierarchical in the sense that principles are placed in a meaningful order according to central concepts, and whether they are from translational, rotational, or fluid mechanics. We use the word "principle" to refer to all the equations that are not mere definitions. To some degree, the organization of HPSM also reflects the textbook for the course [37]. Rawson and Dunlosky [38] remarked that memorization should probably be constrained to key concepts that provide the foundation for further learning. Novice students, particularly the weaker students, also lack cohesion in their domain knowledge [39]. HPSM can help make clear what the essential principles and definitions are and help integrate domain knowledge that might seem fragmented to a novice student. Most physics students are familiar with cramming sheets, as it is a normal practice to allow a set number of handwritten sheets for exams. A quick internet search reveals numerous examples of physics cramming sheets, some from commercial actors but most made by students. However, these cramming sheets usually lack meaningful organization and rather reflect students' effort to include every equation and some diagrams. Others, such as those in physics textbooks, are usually in the form of tables of constants, concepts, and equations. The novelty in our study is in the hierarchical structuring of HPSM, reduction to the essential principles and definitions, and in integrating retrieval practice of HPSM into regular lectures (phase 2).

As already mentioned, research on retrieval practice in physics is scant. This study can be viewed as an early step towards finding a role for retrieval practice in physics education. We introduce retrieval practice of HPSM in two phases, where we explore five research questions. In the first phase, we performed a randomized controlled trial to find (i) whether 70 min of retrieval practice of HPSM improves basic factual knowledge compared to studying problems and (ii) whether students lack knowledge of basic facts after the concepts have been introduced through lectures and problem solving. In the second phase, we implemented longitudinal retrieval practice in physics lectures to explore (iii) whether participation correlates with basic factual knowledge or (iv) with exam results. We also collected exam results in phase 2 and could therefore answer (v) whether scores on basic factual knowledge correlate with exam scores.

II. METHODS

This study took place over two semesters in a calculus-based introductory mechanics course at the University of Bergen. The course participants came from a mixture of disciplines (Physics, Teacher Education, Nano Technology, Ocean Technology, Energy, and Petroleum Technology). Most have completed two years of physics at the high school level.

Phase 1 of the study was a randomized controlled trial comparing retrieval practice (intervention group) with studying physics problems (control group). We expected large effects of retrieval practice on a test of factual knowledge compared to control. A power analysis using GPower [40] with a large effect size of $d = 0.8$ and alpha level of 5%, suggested a minimum of 42 participants to achieve a power of 80% for detecting an effect.

The experiment was conducted during a regular lecture and participation was voluntary and anonymous. 81 students showed up out of the roughly 150 students signed up for the course. All participants had equal chances of winning a gift certificate of 2000 NOK (~250 usd) at the end of the experiment. All the concepts in the course curriculum had been covered in lectures before the experiment took place. The intervention group did 70 min of written retrieval practice of the hierarchical principle structure for mechanics (see Supplemental Material [36] for the current version of HPSM) on a worksheet where parts of the HPSM were removed. The worksheet consisted of 8 pages where parts of the HPSM had been progressively removed. The students received instructions to retrieve from memory and write down the missing parts. Some parts of HPSM were marked as not relevant (kinematics and fluid mechanics). The control group studied nine pairs of problems from the similarity judgment task (Appendix 1 in Ref. [41]). The nine problems covered the same concepts as the retrieval practice. The full HPSM was available during practice for both groups. Students in both groups had 20 min to first complete a filler post-test after completing the practice phase to get a better measure of long-term memory. Then, the students had 10 min to complete the declarative facts test which consisted of 20 questions.

What is/are the unit(s) of

1. Force
2. Energy
3. Work
4. Linear momentum
5. Angular momentum
6. Torque

Write an expression for

7. Newton's second law
8. Work when force is constant
9. Conservation of mechanical energy
10. Conservation of energy, non-conservative forces included
11. The work-energy theorem.
12. The impulse-momentum theorem
13. Linear momentum
14. The angular momentum of a particle
15. The angular momentum of a rotating object
16. Gravitational potential energy
17. Spring potential energy
18. The force of friction

What are the conditions for

19. Conservation of linear momentum
20. Conservation of angular momentum

The first author constructed the test. The three authors, who all have at least five years of physics at university level and who all have taught physics, agreed that the test questions probe essential basic facts from mechanics. Cronbach's alpha for these 20 items was 0.89 in phase 1 and 0.87 in phase 2, indicating good internal consistency.

Phase 2 of the study was correlational, and was in part motivated by the results in phase 1 and promising results in Ref. [15]. We implemented distributed retrieval practice in the lectures of the same course as in phase 1, but in the subsequent year. The students completed 15 min of retrieval practice in the beginning of 16 of the lectures. Apart from the retrieval practice, the lectures mostly consisted of traditional lecturing and some weekly quizzes with conceptual questions and a peer instruction format [42]. Our participants were those students who decided to show up for lectures, which were not mandatory. In total, 130 students participated in retrieval practice at least once. The study sample in phase 2 consisted of approximately 35% females, 65% males, and 21% nano technology, 18% ocean technology, 13% physics, 13% energy, 9% teacher education, 7% petroleum technology, and 19% other, with a mean age of 21. The average show up was 53 students (SD = 24), roughly reflecting how many typically show up for voluntary lectures at the institute. Each written work (retrieval sheet) handed in counted as one lot for a lottery of three gift certificates (~110$ each). The students could participate in all activities regardless of whether they chose to hand in their written material for analysis. The retrieval practice was performed on two-sided retrieval sheets where the equations, their names, and their conditions of application were removed from HPSM. The full HPSM was available during retrieval practice for feedback and restudy opportunity. Advice for how to do the retrieval practice was visible on a projector screen while the students practiced (see Supplemental Material [36] for the advice given to students and the literature the advice was based on). We tested the students on the same declarative facts test as in phase 1, but 37 days earlier in the semester. Furthermore, in phase 2 we obtained final exam scores for 90 students and prior Calculus 1 grades as a measure of prior ability for 83 of these 90 students. The final exam consisted of regular word problems and a few conceptual multiple-choice questions. We obtained exam results for 28 of the 34 students that completed the declarative facts test.

The data from the RCT in phase 1 was analyzed with a t test, with Cohen's d as a measure of the effect size. The data from phase 2 was analyzed with simple correlational analysis and regression. An important confounder in phase 2 is the fact that students also participated in the lectures when they did retrieval practice. Therefore, any correlations with performance in phase 2 needs to be interpreted with caution.

III. RESULTS

A. Phase 1—RCT

For reference, Cohen's d effect sizes of about 0.20, 0.50, and 0.80 are usually treated as small, medium, and large, respectively [43]. Hattie [44] proposes that effect sizes of 0.40 or higher are educationally relevant, although one must also consider ease of implementation.

A two-tailed t test was performed to determine whether retrieval practice significantly affected basic factual knowledge compared to problem study. The t test showed a significant effect of retrieval practice for score on the declarative facts test ($M = 14.6$, $SD = 3.6$) compared to control ($M = 9.0$, $SD = 4.3$), $t(77.5) = 6.4$, $p < 0.001$, $d = 1.42$, a very large effect.

B. Phase 2—Correlational

Roughly a third of psychological meta studies have $r < 0.20$, the middle third has r of 0.20–0.30, and the upper third have $r > 0.30$ [45,46]. We use these numbers as empirical guidelines for small, medium, and large effect sizes.

We calculated the Pearson correlation coefficients to find whether number of retrieval practice sessions attended correlated with score on the facts test and final exam score, and whether the facts test correlated with final exam score (research question 3, 4, and 5). All correlations were significant, see Table I (see Figs. 4, 5, and Fig. S6 in the Supplemental Material [36] for scatter plots). Moreover, a scatter plot of retrieval practice sessions vs exam score suggested a possible interaction between attending retrieval practice sessions and ability, where high-ability students do well regardless of whether they attend lectures with retrieval practice. A multiple linear regression was therefore calculated to predict the physics exam grade with Calculus 1 exam grade, the number of retrieval sessions attended, and the interaction as predictors. A significant regression equation was found [$F(3,79) = 18.73$, $p < 0.001$], with an $R^2 = 0.42$ and adjusted $R^2 = 0.39$, see Table II. Both main effects were significant, but more importantly the interaction term was significant. In other words, weak students seem to benefit while strong students do well regardless.

IV. DISCUSSION

Answering research question 1, the RCT in phase 1 showed that 70 min of retrieval practice can be far more efficient than "just studying" for learning physics facts ($d = 1.42$). That retrieval practice is better than studying for a factual test is not surprising, but the effect is remarkably large. As implementation is easy, it seems ready for use in physics education. In answering research question 2—whether students actually lack knowledge of basic physics facts—we qualitatively evaluate the control group's mean score of 9 correct answers to be very low when considering the low difficulty of the test items. Physics students lack the most basic knowledge.

In phase 2, the very high correlation ($r = 0.62$) between score on the factual test and the final exam suggests that knowledge of basic facts is important in introductory mechanics (research question 5). Participation in lectures with retrieval practice had a high correlation with score on the factual test ($r = 0.44$), which suggests that retrieval practice also affects basic factual knowledge when distributed throughout the semester (research question 3). Still, something goes wrong for some of the students. As an example, one of the students attended seven retrieval practice sessions and still only got two factual questions correct (question 1 and 2) and there were others with similar results. It seems likely that these students either participated to win money, misunderstood the purpose and merely copied equations, or ignored advice.

The correlations in Table I and the regression model in Table II indicate that weaker students (as measured by Calculus 1 grade) benefit more than strong students from lectures with retrieval, while strong students stay strong (research question 4). Retrieval practice of principles and definitions may be an effective way to reduce the gap between weak and strong students by strengthening the weak.

We speculate that some elaboration, and possibly time for consolidation, is essential for getting maximum benefits from retrieval practice [21]. Many students retrieved principles without any prior elaborative encoding in phase 2, and some students did complain about lack of understanding of retrieved principles. We thought that students would try to encode the principles elaboratively without specific support, but it seems that some support is needed.

In hindsight, we probably made it unnecessarily difficult to memorize HPSM in phase 2 by removing every cue except spatial location. Vaughn and Rawson [47] found that cued retrieval practice enhances memory for both the memory cue and the target memory, enhancing associative memory in both directions although slightly more in the practiced direction. This might justify doing only forward recall of equations from name, conditions, and location. Retrieval of the equation from the name and the condition of application for the principle is also more aligned with what happens in problem-solving situations, which is

TABLE I. Correlations between retrieval practice sessions attended, the declarative facts test, and final exam score.

Relationship	r	t value	df	p
Retrieval practice—facts test score	0.44	2.74	32	<0.01
Retrieval practice—exam score	0.33	3.29	88	<0.01
Facts test score—exam score	0.62	4.06	26	<0.001

TABLE II. Multiple linear regression of Calculus 1 grade and retrieval sessions attended as predictors of exam grade, $N = 82$.

	ΔR^2	B	SE B	p
Step 1	0.42			
Constant		1.65	0.54	<0.01
Calculus 1 grade		0.71	0.14	<0.001
Retrieval sessions		0.17	0.08	<0.05
Calculus*retrieval		−0.04	0.02	<0.05

important for transfer to occur [25]. Students may also become more motivated to use retrieval practice as they experience quicker success [38]. We also constrained the students to retrieval of current concepts, with some opportunity for repetition of prior concepts. Providing the full HPSM on both sides of the retrieval sheet grants the student greater flexibility in what to study and retrieve, and probably improves learning of spatial locations (see Supplemental Material [36] for the current version of the retrieval sheets).

V. CONCLUSIONS

In phase 1 of this study, we showed that (control) students in introductory mechanics have a grave lack in basic factual knowledge, and that a short intervention with retrieval practice of a hierarchical principle structure can dramatically increase scores on a declarative facts test. In phase 2, we implemented distributed retrieval practice in lectures throughout the semester. Results indicate that knowledge of basic facts predicts exam score, and that especially the weaker students benefit from attending lectures with retrieval practice.

More research is needed on how to better integrate the hierarchical principle structure into a course and how to support elaborative encoding, which will probably potentiate the effects of retrieval practice [21]. There is also a need for experimental testing of whether lectures with distributed retrieval practice is superior to lectures without, and for what measures.

We speculate that HPSM has a potential—beyond retrieval practice—as an organizing tool for lectures and other learning activities. However, testing this would require a different theoretical framework and research design.

ACKNOWLEDGMENTS

This work was supported by the University of Bergen.

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Supplementary material for

Gjerde, V., Holst, B., & Kolstø, S. D. *Making stronger students: Retrieval practice of a hierarchical principle structure in university introductory physics*.

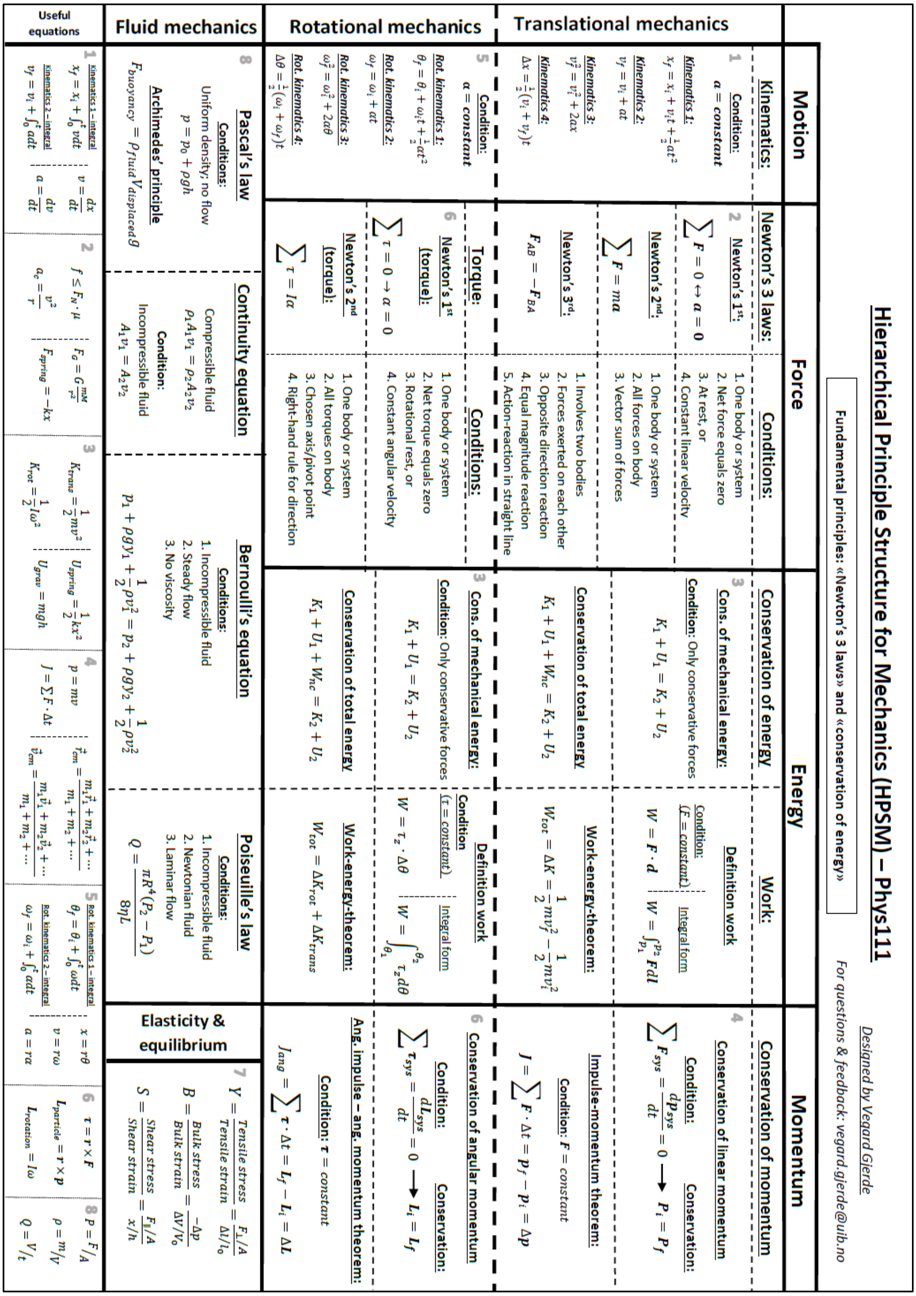

Figure 1 - The current version of the Hierarchical Principle Structure for Mechanics (HPSM).

Symbol	Name	SI Units
t:	Time	s
x:	Distance	m
v:	Velocity/speed	$^{m}/_{s}$
a:	Acceleration	$^{m}/_{s^2}$
F:	Force	$N = Newton = kg\ ^{m}/_{s^2}$
k:	Spring constant	$^{N}/_{m}$
μ:	Coefficient of friction	NA
f:	Frictional force	N
a_c:	Centripetal acceleration	$^{m}/_{s^2}$
G:	Gravitational constant	$6.67 * 10^{-11}\ m^3 kg^{-1} s^{-2}$
K:	Kinetic energy	$J = Joule = kg\ ^{m^2}/_{s^2}$
U:	Potential energy	J
W:	Work	J
W_{nc}:	Work by non-conservative forces	J
d:	Distance	m
P:	Total linear momentum	$kg\ ^{m}/_{s}$
p:	Momentum of object	$kg\ ^{m}/_{s}$
J:	Impulse	$kg\ ^{m}/_{s}$
θ:	Angle/Angular displacement	rad
ω:	Angular speed/frequency	$^{rad}/_{s}$
α:	Angular acceleration	$^{rad}/_{s^2}$
τ:	Torque	$kg\ ^{m^2}/_{s^2}$
I:	Moment of inertia	$kg * m^2$
L:	Angular momentum	$kg\ ^{m^2}/_{s}$
ρ:	Density	$kg * m^{-3}$
p:	Pressure	$Pa = Pascal$
η:	Viscosity	$Pa * s$
Y:	Young's modulus	Pa
B:	Bulk modulus	Pa
S:	Shear modulus	Pa

Questions for Elaborative Encoding

Think about or discuss these questions to develop understanding of each principle and definition in HPSM.

For each principle and definition,

Detail-level

1. Which concepts and units belong to its symbols?
2. What do these concepts mean?

Principle & equation-level

1. What is its name and why?
2. What is its condition of application?
3. Why is this a condition of its application?
4. What is the meaning of each part of the equation?
5. What happens if one of its variables change size?

Hierarchy-level

1. What is the name of the row and the column it is placed in?
2. Which similarities or dissimilarities to the other principles do you notice?
3. It is empirical or can it be deduced from other principles in HPSM? How?

Figure 2 - Back side of the current version of the Hierarchical Principle Structure for Mechanics (HPSM), including elaborative encoding prompts.

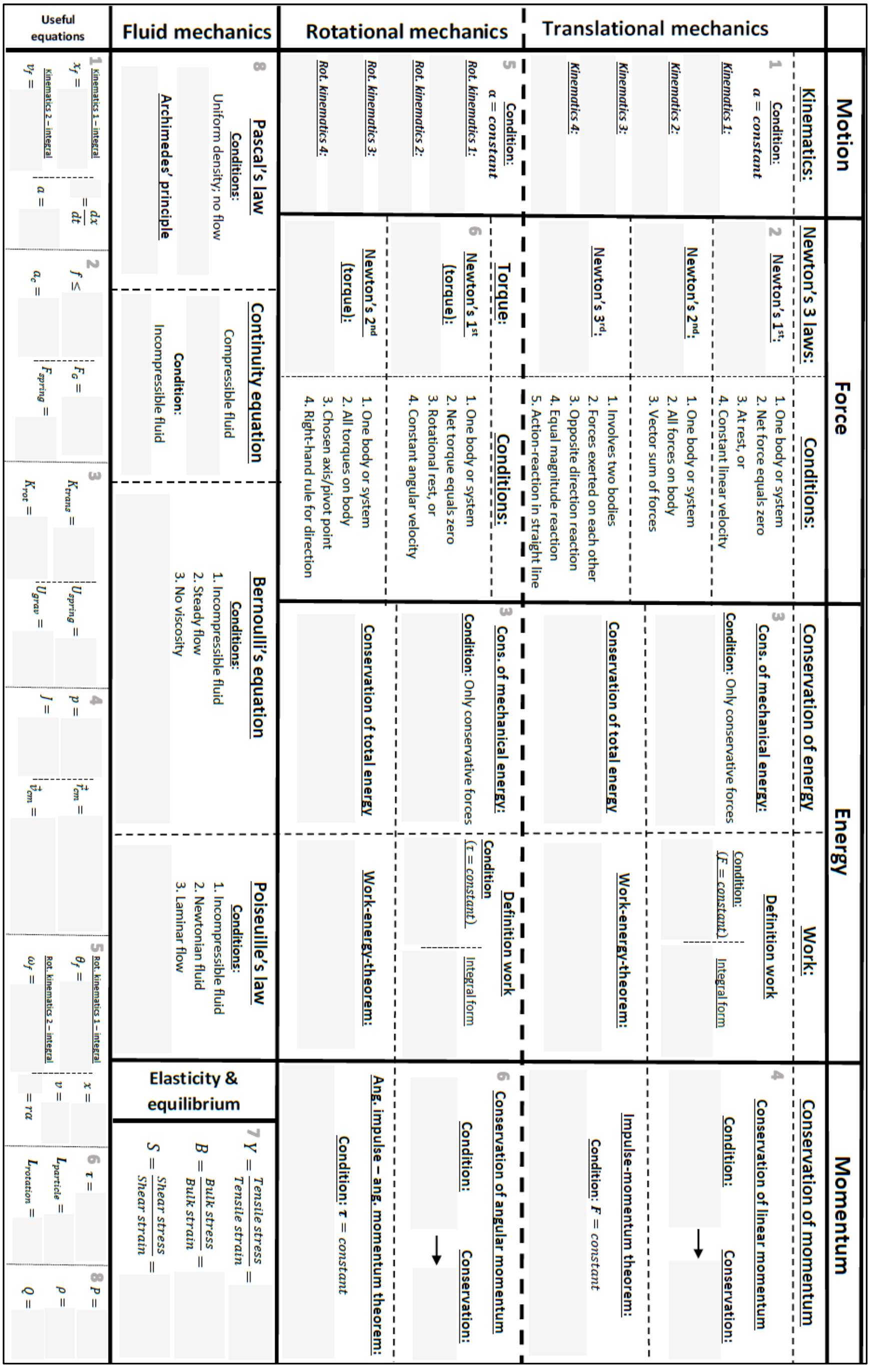

Figure 3 – The latest version of the retrieval sheets

Graphs of relationships

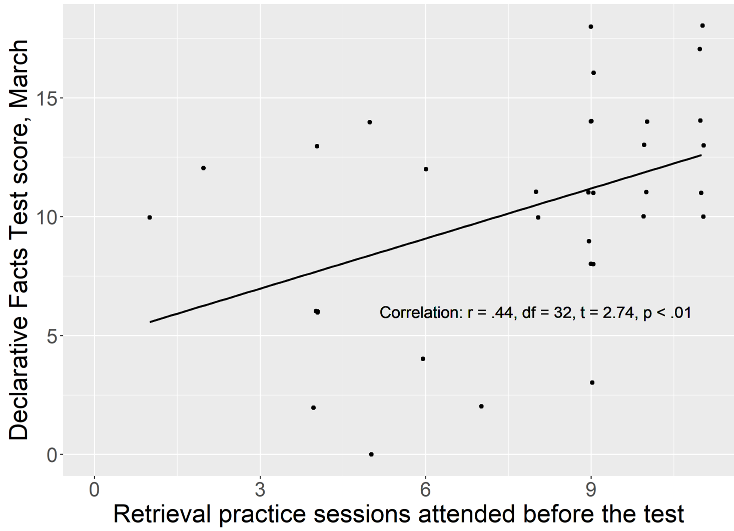

Figure 4 - Scatter plot of score on the declarative facts test vs. number of retrieval sessions attended before the test

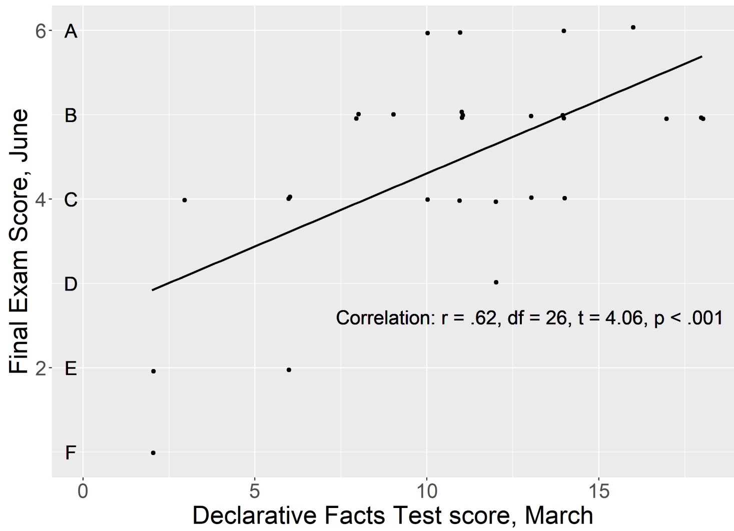

Figure 5 - Scatter plot of final exam score vs. score on the declarative facts test

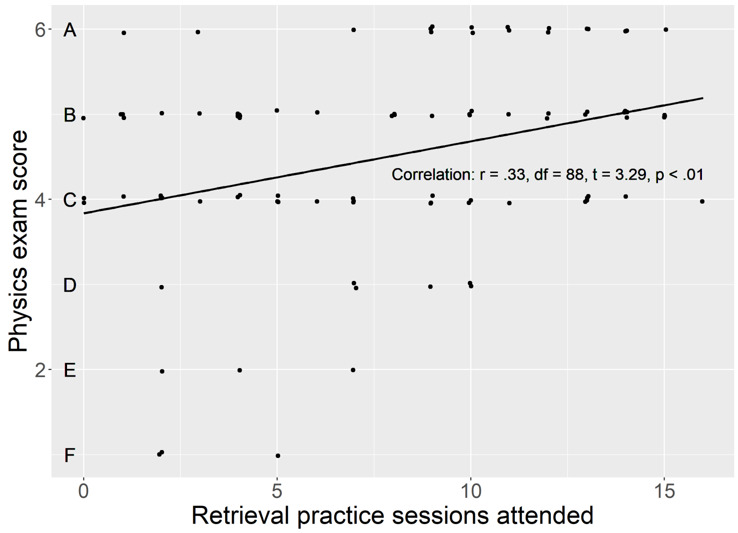

Figure 6 - Scatter plot of score on exam vs. number of retrieval sessions attended

Advice for retrieval practice given to students in study 2

During the retrieval practice sessions, the students were presented with a list of advice projected on a screen. The references provided were the basis for including the advice. The advice we give to students during retrieval has changed after these experiments took place based on the experience gained and continued literature study. The 'updated advice' is also included below with references.

List of retrieval advice (this study)

- Fill in as much as you can remember (retrieve memories) [1]
- First try to retrieve your weakest memories [1]
- Reduce switching between retrieval and (re-)study by retrieving everything first [2-4]
- Re-study when you go 15-30s without remembering more [1]
- Place a checkmark where you have remembered a fact 3 times within the same session [5-7]
- Retrieval is most effective when successful, re-study is most effective after retrieval failure [1, 8, 9]

Updated advice for retrieval practice

We include this updated advice for physics educators who wish to incorporate retrieval practice in their own lectures.

The advice for retrieval practice has been changed based on feedback from students and continued reading of the retrieval practice literature, particularly the literature on the interplay between elaborative encoding and retrieval practice. We proposed in the discussion section of the article that retrieval practice may be potentiated through support for elaborative encoding. Therefore, we have included question prompts for elaborative encoding

Retrieval advice

- First, fill in as much as you can remember (retrieve memories) [1]

    - If you have remembered a whole HPSM-box in at least 4 retrieval sessions, and you feel confident for future retrievals, you can skip it this session and place a checkmark in that box. [5-7]
- Retrieval is most effective when successful, re-study is most effective after retrieval failure [1, 8, 9]
- When you go 15-30s without remembering more old items (previously studied) [1]:
    - 1. Restudy and mentally retrieve failed items)
    - 2. Write down the mentally retrieved items
    - 3. Repeat 1 and 2 until all the failed have been retrieved
- Elaboratively encode one new HPSM-box at a time, and [9-16]:
    - 1. Do written retrieval of the new material
    - 2. Do mental retrieval+immediate feedback until successful
    - 3. Write down the items you didn't remember in step 1
- Make time for rehearsal of the 'new' facts [1, 7]

Elaborative encoding-questions

The following elaborative encoding questions are visible during our current retrieval practice sessions. They are a subset of the elaborative encoding questions on the back of HPSM, see Figure 2 above. The questions are based on [10, 11, 17, 18], the structure of HPSM (see article), and a subjective assessment of relevant elaborations. These questions were not part of the study but are rather part of our continued attempt to help students memorize in a meaningful way:

Start from the first question you are unable to answer and continue until you think you will be able to retrieve the principle/equation:

Detail-level

1. Which concepts and units belong to its symbols?

Principle&equation-level

1. What is its name and why?
2. What is its condition of application?
3. What happens if one of its variables change size?

Hierarchy-level

1. What is the name of the row and the column it is placed in?
2. Which similarities or dissimilarities to the other principles do you notice?

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Paper 1

Paper 2

Paper 3

Integrating Effective Learning Strategies in Basic Physics Lectures: A Thematic analysis

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Introductory mechanics is taught worldwide. It is an obligatory course for many disciplines outside of physics and the failure rate is often high. Furthermore, as pointed out by Mazur and others, even the students who pass the course often fail to achieve the main learning goal: The conceptual knowledge required for modeling situations with physics principles. In many cases, this is not due to a lack of devoted study time but rather due to inefficient learning strategies. Therefore, we integrated three established learning strategies from cognitive science and educational psychology into the structure of an introductory mechanics course: Elaborative encoding, retrieval practice, and self-explanation. We also developed three scaffolding tools to facilitate the integration of the strategies: Elaborative encoding-questions, a hierarchical principle structure, and a problem-solution structure with emphasis on physics modeling. Our study differs from other studies on learning strategies in that we integrate strategies within a course, ensuring widespread exposure to strategies that are transferrable to other courses. A basic assumption of this work is that the learning strategies are effective if students actually use them. Thus, the overarching aim of this study is to use students' experience-based reflections to find ways to improve the integration of the learning strategies, such that students use them and use them effectively. To fulfill this aim, we must find answers to the following three interrelated research questions: (1) What are the students' experiences and associated reflections with the learning strategies and tools? (2) How do the students' experiences and reflections align with established theory on the learning strategies? (3) What main barriers to effective implementation of the learning strategies may be hypothesized? To answer these questions, we did semi-structured research interviews with 12 students, spanning the entire range of grades on the final exam. Through the thematic analysis we found that students almost invariably ignored the elaborative encoding-questions; that few students self-explain solutions to problems, partly because of the required mental effort and implicit beliefs that one should avoid studying the solutions; and that, while most students participated at least once in structured retrieval practice, only some students found retrieval practice beneficial and motivating. The analysis, together with theoretical considerations, indicates that successful implementation of elaborative encoding is critical for maximizing the benefits from retrieval practice in physics. We also present some emergent and promising findings on two of the tools: i) Students' extensive use of the hierarchical principle structure and ii) some students started practicing physics modeling after exposure to the solution structure. Finally, we offer suggestions for how to overcome the barriers and build on facilitating aspects of effective implementation of each of the learning strategies.

I. INTRODUCTION

Learning how to model a situation with physics is arguably the most important thing physics students can learn [1, 2]. When students make an effort to model the situation in a problem by using physics principles, they activate and contextualize prior knowledge, deepening their conceptual understanding. For reference, we use physics principles to refer to both the fundamental principles (Newtons' Laws and conservation of energy) and derivable principles (e.g. work-energy theorem). However, many physics students use a formula-hunting, plug-and-chug approach to problem-solving [3, 4]. Consequently, many students fail to acquire conceptual knowledge [5, 6], even after finishing courses at prestigious universities [7, 8] and even after solving hundreds of physics problems [9]. Many physics students are not even able to reproduce Newton's second law, the work-energy theorem, or other important physics principles a few weeks before the final exam in mechanics [10]. Consequently, the failure rate is often high and the main learning goals are not achieved, even if the students have devoted a considerable amount of study time.

Cognitive science and educational psychology, together with physics education research, provide many insights into the cognitive knowledge structure students need to acquire for physics principles. For example, students need to build useful associative links within and between physics principles [11-13]; they need to build adequate memory strength for physics principles [10, 11]; they need to integrate physics principles into a hierarchical cognitive structure [11, 13-15]; they need to build the conceptual knowledge required for physics modeling when studying worked examples [16-18]; and they need to learn how to model a situation with physics principles [1, 15, 19, 20]. Cognitive science and educational psychology can provide learning strategies that are well-suited for stimulating learning on all these levels [e.g. 21, 22]. However, there is a lack of translation from basic research to the teaching of physics [23].

There have been numerous attempts at intervening in students' use of learning strategies in higher education. However, students often hold widespread beliefs and illusions about learning that hinders them from becoming self-regulated users of effective learning strategies [24]. They may also struggle to transfer the learnings from one-off interventions from outside the classroom to inside the classroom [25] and, although they often intend to use effective learning strategies, many fail to follow through with their intentions [26]. Many students tend to prefer ineffective learning strategies—e.g. reading, copying, and highlighting lecture notes [26]—over effective learning strategies [27-29], even when given direct instruction in the relative effectiveness of learning strategies and when given evidence that their performance improved with effective strategies [30]. Yan, Bjork [30] argued that the three main reasons for students' persistent misconceptions of learning were the sense of fluency associated with ineffective strategies, pre-existing beliefs, and thoughts about unique learning styles.

There seems to be a growing consensus that training inside the context of the classroom is superior to interventions outside of the classroom [25, 31, 32]. However, few studies on learning strategies are conducted in authentic classroom settings [33, 34]. Fewer still implement multiple learning strategies. A rare exception being Gurung and Burns [35] who implemented two learning strategies—retrieval practice and distributed practice—in an authentic setting. Biwer, Egbrink [36] used a 6-hour intervention, outside of the classroom, to foster students' awareness, reflection, and practice of multiple learning strategies in medical sciences. The qualitative findings suggested that student adoption was impeded by the students' uncertainties about effort and time management, lack of available material, and lack of knowledge of how to implement the learning strategies. Also outside of the classroom, Endres, Leber [37] tried to follow multiple proven principles for strategy-interventions [38] in their digital learning environment, such as implementation intentions [39] and principles for multimedia learning [40]. Still, most students continued with suboptimal studying.

In addition to the challenges mentioned above, it is difficult to teach students the relevant and necessary knowledge about the learning strategies. Moreover, it is difficult to bridge the gap from correct knowledge to actual usage of the learning strategies [30], especially when introducing multiple learning strategies [36]. Further, the structure of the domain knowledge is opaque to the students [41], making it difficult for them to find and use suitable educational resources.

Basic learning strategies can potentiate more complex learning strategies. For example, elaborative encoding can potentiate retrieval practice, retrieval practice can potentiate self-explanations, and self-explanations can potentiate problem-solving. This is an important reason why simultaneous integration of several strategies is critical for achieving the potential of each strategy. Integration is also important for identifying relevant barriers and facilitators for each learning strategy. See section I, A-C for further discussion on how the learning strategies potentiate each other.

In this study, we integrated three established learning strategies into two existing learning arenas of an introductory mechanics course: Lectures and a problem-solving seminar. We developed three scaffolding tools to facilitate the integration. By integrating learning strategies into the learning arenas of a course, we ensure that more students get exposure and practice over an extended period of time, with the possibility of slowly changing their study habits. Specifically, the three strategies were elaborative encoding for learning useful associative links within and between physics principles; retrieval practice for strengthening the memories of physics principles; and self-explanation for learning the conceptual knowledge required for physics modeling during problem-solving. The three associated scaffolding tools were a set of questions for supporting elaborative encoding, the Hierarchical Principle Structure for Mechanics [10], and a problem-solution structure with emphasis on physics modeling, see Supplemental Material at [URL will be inserted by publisher] for more information on the scaffolding tools. Prior work has shown that retrieval practice of the Hierarchical Principle Structure for Mechanics is beneficial for the performance of physics students [10]. Our study differs from this and other studies on learning strategies in that we integrate multiple strategies into lectures, all intended to synergize, and that we focus on effective implementation.

This study is not a test of whether these learning strategies work in physics. An important assumption of our work is that the presented learning strategies are indeed effective, as shown by basic cognitive science and educational psychology [e.g. 21, 22, 42]. The overarching purpose of this study is to investigate how to effectively implement the integration of these strategies and tools into introductory physics courses, especially by identifying important barriers and facilitators.

In order to achieve our purpose, we pursue three interrelated research questions: (1) What are the students' experiences and associated reflections with the learning strategies and tools? (2) How do the students' experiences and reflections align with established theory on the learning strategies? (3) What main barriers to effective implementation of the learning strategies may be hypothesized? To answer these questions, we used thematic analysis [43] to qualitatively analyze semi-structured research interviews with 12 students. Qualitative analysis is an established tool for investigating the processes of an intervention [44]. We use the framework of knowing what to do when, why, and how ["WWW&H", e.g. 31, 45]—important aspects of self-regulated learning—for comparing students' metacognitive knowledge of the learning strategies with established theory. The university was shut down because of the Covid-19 pandemic eighth weeks into the 22-week semester. This changed the study into a two-month intervention, where they lost access to some of the structured learning arenas and self-regulated use of learning strategies became more important.

In the next sections, we introduce the three learning strategies elaborative encoding, retrieval practice, and self-explanations. The scaffolding tools are briefly discussed in the methods section.

A. Learning Strategy 1: Elaborative Encoding

Elaborative encoding is to deliberately search for connections between knowledge units, to create redundancy of retrieval cues to the memory and redundancy of inference pathways to the memory [46]. Elaborative encoding works best when students create highly integrated, plentiful, meaningful, and predictive associative links [46-48]. This can be done by answering guiding questions that are intended to stimulate elaborative encoding [49]. An example elaborative encoding-question is, "What happens if one variable in the principle changes size?".

When students first start learning new physics principles, they lack meaningful associations between the symbols and terms within the equations and they lack meaningful associations between principles [47]. Therefore, students have to rely on cue strength, which they also lack, to be able to retrieve a weak memory [50]. Creating meaningful connections within and between principles gives students more direct retrieval pathways and more ways to reconstruct weak memories during retrieval practice [12, 46]. Hence, we believe that elaborative encoding of physics principles can potentiate retrieval practice through the creation of intra- and inter-item associations because it enables mental reconstruction of the memory [12, 48] and increases the retrieval success rate during retrieval practice [51-53]. Self-evidently, meaningful associative links within and between physics principles are also important for achieving mastery of physics modeling.

B. Learning Strategy 2: Retrieval Practice

Retrieval practice is a learning strategy where one purposefully retrieves memories in order to strengthen them and increase the likelihood of being able to recall them at a later stage, e.g. being able to recall Newtons' three laws. Retrieving a memory adds more strength to the memory compared to restudy [54] because, unlike restudy, retrieval is a gradual process of reconstructing the memory thereby increasing the strength of intra-item associations [12, 55]. The increased memory strength from retrieval practice improves memory accessibility [50], makes retrieval of the memory less dependent on cues from the environment [12, 50], spares working memory capacity [56-58], improves retrieval fluency [59], and improves transfer to new contexts [34, 60-62]. Despite the proven benefits of retrieval practice in many domains [21, 22], little research has been done on retrieval practice in physics until recently [10, 17, 23].

Retrieval practice of physics principles and their conditions of application can potentiate other learning strategies [63-65]. It can reduce the failure rate and time spent floundering during problem-solving, especially during physics modeling [66]; it can improve the quality of students problem-solving by shifting their focus to the conditions of application of principles [17]; it can improve the quality of students' self-explanations [17] through increased prior knowledge and knowledge access [67-69]; and we speculate that it can also improve the effectiveness of other learning activities, such as reading and attending lectures.

Novice students typically lack cohesion in their knowledge [41]. Some research suggests that a hierarchical structuring of memories enables direct encoding into long-term memory, thereby extending the capacity of working memory through long-term working memory [14]. Gjerde, Holst [10] used the meaningful connections between physics principles in mechanics to create a Hierarchical Principle Structure for Mechanics, which their students used in retrieval practice. We believe that this is a superior option to using tables, flashcards, or any other structuring of the retrieval-material that fails to meaningfully organize the content knowledge.

C. Learning Strategy 3: Self-Explanations

Self-explanation is to explain the steps in a worked example in order to learn how to solve problems. For example, one can explain the physics model in a worked example by identifying the underlying physics principle(s), explicating the conditions of application, and describing how the mathematical equations are set-up and why [16, 17, 70]. Self-explanation results in the creation of abstract rules for problem-solving that can be retrieved and interpreted during problem-solving and in direct memories of parts of worked examples that can be retrieved and used analogically [16, 17, 71]. The abstract rules provide context, direction, and depth to problem-solving actions [17, 71], building the conceptual knowledge base required to model physical situations.

High-quality self-explanation—self-explanations that explicate principles, conditions of actions, and goals for the action-steps in worked examples—can potentiate problem-solving, especially helping students learn how to solve conceptually challenging problems [16, 17, 72]. Self-explanation increases students' reliance on prior knowledge [67-69], and may therefore synergize with retrieval practice of physics principles by converting strong memories of physics principles into useful conceptual knowledge [17]. Finally, a major contributor to many students' low learning efficiency during problem-solving is time spent floundering [51, 73]. Self-explanations can reduce students' floundering through prior self-explained worked examples, but also through treating the problem they are currently stuck on as a worked example (given that the solution is readily available).

II. METHODS

A. Participants

The intervention was implemented in an introductory mechanics course with approximately 150 students enrolled. There were 12 interview participants, seven females, five males, and a mean age of 21 years (range: 19-28). There were four students from physics, two from energy, two from geophysics, one from ocean technology, one from nanotechnology, one from teacher education, and one other. There was also a wide range in previous calculus grades (F to B) and final exam scores in mechanics (19-98 percentage points). The study was approved by the Norwegian Centre for Research Data and all the participants provided informed consent.

B. The Learning Strategy Integration Intervention

We integrated the three learning strategies into lectures and a problem-solving seminar. The existing structure of the lectures was a mix of traditional lecturing and Peer Instruction with conceptual problems [7]. Peer Instruction is a useful way to focus students' attention on the relevant physics principles, as conceptual problems are often designed to reduce the need for mathematics. We kept the existing lecture structure but reduced the traditional lecturing.

We used the first lecture of the semester to briefly inform students about what the learning strategies are, why they improve learning, and how and when they should be used. We also presented some of our results from prior semesters and some important results from the literature. Finally, we told them about the results in the literature of how students tend to prefer lectures and strategies that feel fluent and effortless but which ultimately result in less learning than more effortful and active lectures and strategies [74, 75].

1. Elaborative encoding and retrieval practice integrated into lectures

The students participated in structured elaborative encoding and retrieval practice of physics principles, using the Hierarchical Principle Structure for Mechanics (scaffolding tool), for the first 15 minutes of a weekly lecture. The students were advised on how to maximize the effectiveness of the retrieval practice through advice on a projector screen and a short instructional video on how to do retrieval practice. The elaborative encoding-questions were adjacent to the retrieval practice-advice on the projector screen. These questions were intended as a scaffold for creating associative links within and between principles we had not yet covered and for principles they were unfamiliar with. The retrieval practice-advice provided suggestions for when they should spend time answering the elaborative encoding-questions. Students performed the retrieval practice on a sheet of paper where all the equations had been fully or partly removed from the hierarchical principle structure. Every student had the full hierarchical principle structure available for feedback and restudy. Students were told that we expected them to do retrieval practice on the material that had already been covered in lectures, but that they could go beyond this if they wanted to. To model a way to answer the elaborative encoding-questions, we uploaded example Q&As for five important principles and notified students of this with an announcement on the student portal. See Supplemental Material at [URL will be inserted by publisher] for the elaborative encoding-questions, an example Q&A for elaborative encoding, the Hierarchical Principle Structure for Mechanics, the retrieval sheets, and the retrieval practice-advice.

2. Self-explanation integrated into seminars

Self-explanation was integrated into a weekly two-hour seminar on problem-solving. The students received four weekly seminar problems as voluntary homework one week prior to the seminars. The problems were almost all multiple-equation problems and generally not broken-into-parts [problems from 76]. The solution sheet was uploaded immediately after the seminar. The solutions were structured in a way to emphasize the different phases of problem-solving, which has been found to facilitate students' understanding and transfer [73, 77] and they contained no instructional explanations to avoid suppressing self-explanation activity [78]. Specifically, we structured the solutions according to the following five steps: (i) Initial coding of the problem by identifying the goal(s) and given variables, (ii) constructing a diagram and/or a picture, (iii) modeling the problem with physics principles, (iv) solving the problem by doing mathematical procedures on the physics model, and (v) reflecting on the solution. See Supplemental Material at [URL will be inserted by publisher] for an example solution following this structure.

The structure of the seminar was roughly as following: 10 minutes of individual written self-explanation of a worked example, subsequently explained by the seminar leader for 5 minutes; followed by 60 minutes of going through the four seminar problems, with about 5 minutes for each problem allocated to let students explain the physics model, to themselves or to peers, before the seminar leader presented his explanation of the physics model; and, finally, 15 minutes where students attempted to solve a new problem by using the presented solution structure and the seminar leader gradually showed his solution.

C. Interview procedures

The semi-structured research interviews were conducted digitally with an interview guide by the third author. This was to reduce potential bias due to students' familiarity with the first author (problem-solving seminar leader) and the second author (the lecturer). The interview guide consisted of questions that probed students' experiences and reflections of the different learning strategies and tools, see Supplemental Material at [URL will be inserted by publisher] for the interview guide. The interviews were transcribed intelligent verbatim by a company offering specialized transcription service, with a confidentiality agreement.

D. Data Analysis

We used a variant of the thematic analysis method laid out by Braun and Clarke [43]. The analysis was performed in the software NVivo [79]. Our thematic analysis identified themes explicating and naming meanings expressed by the students, with some themes representing our interpretation of the underlying meaning of the students' utterances. We counted as a theme anything that captured important aspects related to our research questions, especially looking for themes important for improving the integration of the learning strategies and tools. We use the framework of knowing what to do when, why, and how ["WWW&H", e.g. 31, 45] for analyzing the alignment between students' metacognitive knowledge of the learning strategies and established theory. Similar to Biwer, Egbrink [36], we identify potential barriers and facilitating aspects for each of the learning strategies based on the identified themes.

An important theoretical assumption for the analysis is that people are more similar than dissimilar in their learning processes and that supposed learning styles are irrelevant for optimal instruction and learning (prior knowledge is relevant). Further, we are not probing for students' unique insights into learning, rather sticking closely to theoretical models of learning and comparing students' practices and reflections to these ideals.

The general flow of the analysis was as follows: The first author listened to all the audio recordings twice before segmenting the written transcripts into broad categories relating to the different learning strategies and tools. The next step was detailed coding of the students' utterances and identification of themes. These themes were then hierarchically categorized according to tentative themes and then structured visually in a thematic map for each learning strategy. The themes were continually refined during the process—changed, collapsed, or separated—in response to renewed inspections of underlying utterances and themes and any perceived lack in internal coherence or external distinguishability, as recommended by Braun and Clarke [43]. The analysis was also discussed in seminars with the first and last author and three other educational researchers. Finally, the sections with qualitative findings and discussion of the findings were sketched and discussed for possible inconsistencies. The first author listened five times through all the interviews during the process, searching for missed themes and inconsistencies.

III. FINDINGS AND DISCUSSION

In this section, we present the themes regarding students' experiences and reflections with each of the learning strategies (research question 1), connecting the students' experiences and reflections to theory on what to do when, why, and how ["www&h", e.g. 31, 45] and to barriers and facilitating aspects of the implementation (research questions 2 and 3). We also offer suggestions for how to overcome the barriers and build on facilitating aspects of effective implementation of each of the learning strategies. After presenting the findings from the three learning strategies, we present some emergent findings for the solution structure and physics modeling and for the Hierarchical Principle Structure for Mechanics. See Supplemental Material at [URL will be inserted by publisher] for the original quotes in Norwegian.

A. Elaborative encoding

Table I – Themes from students' experiences and reflections on elaborative encoding (EE)

Themes in students' experiences and reflections	Connection to research questions 2 and 3
1. Thinks EE is something else than it is	Lacking knowledge of what it is
2. Better for repetition and testing	Lacking knowledge of when one should use it
3. Too little value, too high cost	Lacking knowledge of why one should use it
4. Ignored EE-questions	Barriers regarding task structure and resources
5. Unaware of uploaded example Q&As	Barriers regarding task structure and resources
6. Unintentionally using EE during self-study	Barriers regarding task structure and resources
7. Overwhelmed by study options	Barriers regarding task structure and resources

1. Themes in students' experiences and reflections with elaborative encoding

Three students had vague notions that elaborative encoding was something else, e.g. explaining solutions to oneself or discussion prompts for problem-solving, and two students believed that elaborative encoding was best for repetition and testing oneself. Five students thought the cost of doing elaborative encoding was too high and that the value was too low, e.g. “It is so much for so little, I think” and “I guess it is because I haven’t felt a need for it. And maybe that I couldn’t bother spending time on it, in a way”.

Almost without exceptions, the students ignored the elaborative encoding-questions and were completely unaware of the example Q&As we had uploaded. However, it appeared that about half the students unintentionally practiced elaborative encoding in their self-study, seemingly without awareness that they were doing what was intended with the elaborative encoding-questions. One student, who tried to say what he did instead of elaborative encoding, explained exactly what the authors intended for the elaborative encoding:

> I think it comes more out of the principle. […] I think I rather use the physical symbols in the formula, or principle, to remember what it really says and how it looks. Instead of going back and looking [at the elaborative encoding-questions], ‘Ok, this equation gives joule, this is then this and this and this.’ I think it is more like that.

Two students cited the overwhelming amount of study options as a reason for not engaging in elaborative encoding.

2. Alignment with theory

Themes 1-3 in **Error! Reference source not found.** indicate that students gained very little metacognitive knowledge of elaborative encoding. They lacked knowledge of when and why one should use elaborative encoding and many even lacked knowledge of what it is. Theme 4 also indicates that some didn’t know how to do it. The pervasive lack of metacognitive knowledge suggests that they also failed to connect elaborative encoding to retrieval practice and that this may have exasperated the problem of rote rehearsal during retrieval practice (see the next section) which is known to be an ineffective strategy [80].

Although it appears that the students lacked metacognitive knowledge of elaborative encoding, it also seems that some students have study-practices that align with theory on how one should do elaborative encoding.

3. Barriers and facilitating aspects

Theme 3 in Table I indicates that we first need to give students clear reasons for engaging in elaborative encoding. Themes 4-7 indicate that there are substantial barriers to overcome regarding the task structure and associated instructional resources. The students’ reluctance to using the questions signals a need for improvement in either the task structure (elaborative encoding during structure retrieval practice), the instructional resource (the questions), or both. Theme 5, 6, and 7 indicate that there is a substantial barrier to overcome regarding students’ need to self-regulate in an environment with many study options. If we do not provide more structure, we fear that only strong students will study effectively. We failed to identify specific facilitating aspects for elaborative encoding.

4. Discussion on future practice

We believe that for elaborative encoding to become effective, we need to develop instructional material that makes it very clear why and how to elaboratively encode physics principles. Based on our findings, it seems unrealistic to get a large proportion of the students to engage in elaborative encoding merely by using direct instruction in metacognitive knowledge and without using structured tasks. Moreover, we need to make this process less effortful and more engaging, preferably removing the need for self-regulation as some students are overwhelmed by the number of study options.

We speculate that it would be fruitful to embed elaborative encoding in a mandatory social learning task [81]. For example, by getting the students to do structured elaborative encoding in randomly generated digital discussion groups, e.g. with mandatory uploading of discussions. We further speculate that this could stimulate more elaborative encoding during self-study, making it more reflective, because the students become more aware of possible intra- and inter-item links. Indeed, one student reported being cognizant of the elaborative encoding-questions while reading the textbook.

We also speculate that elaborative encoding is best implemented as a separate activity prior to retrieval practice [82], both because many students complain about a lack of understanding during retrieval practice and because we want to ensure memory reconstruction during retrieval practice. Students may then learn how to elaboratively encode principles and start using it for learning new principles during structured retrieval practice. Although some students unintentionally practice elaborative encoding in their self-study, we do not know how many do it, when they do it, or how they do it.

B. Retrieval practice

Table II – Themes from students' experiences and reflections on retrieval practice (RP)

Themes in students' experiences and reflections	Connection to research questions 2 and 3
Positive themes	
1. Finds RP increasingly beneficial	Gained knowledge through practice of why one should do RP
2. Finds RP enjoyable and motivating	Facilitating aspect
3. Elaborating connections helps RP	Facilitating aspect
4. Followed RP advice	Facilitating aspect
Negative themes	
5. Ignored RP advice	Barriers regarding task structure and resources
6. Lack of understanding makes RP rote and unhelpful	Barriers regarding task structure and resources
7. Limited or low value of RP	Lacking knowledge of why one should do it

1. Themes in students' experiences and reflections with retrieval practice

About half the students found retrieval practice of the hierarchical principle structure beneficial in various ways. Encouragingly, some students became aware of more subtle benefits like how the increased familiarity helped them understand more complex material and that they had increased (cognitive) accessibility to the principles. One student said:

> Say you know these equations already now, and then you come to a lecture, you've seen the equation before, you don't become like *gasping sound* when you see the equation, but 'oh yeah, that is that and this. Cool, yeah, that is this law.' And then they explain why it's like that, and then just 'oh, yeah. Cool.'

They also reported that the benefits were gradually increasing. Four students reported having continued doing retrieval practice after the Covid-19 shutdown, citing as reasons that they wanted to refresh and maintain knowledge and that it was an effective way to kickstart self-study when willpower was lacking. One student said,

> When you sit at home in a little room all day you can struggle with your concentration. It is hard to start because you know you have to sit for a long time. So, I have often used it [retrieval practice] as a 'this only takes 15 minutes, so you start with that' and then I often

> notice that it is easier to start things. Then I can already put a checkmark that I have done something that day.

Two students also reported continuing to retrieve memories during problem-solving, which is exactly what we intended.

Four students found retrieval practice enjoyable and motivating. They challenged themselves on speed or amount retrieved in a session, finding the challenge-level appropriate, enjoying the obvious progress. When asked about what is most important when memorizing, one student said:

> I am actually bad at it [memorization]. I have never done it [before] because I think it is really boring. Is it incentive you call it? It is fun to fill out a sheet of paper, week after week, to see if you know it. I try to use it as motivation—this week I filled out this much, next week I will fill out more. Then it becomes full eventually.

Three students found that elaborating on connections helps retrieval practice. One student said:

> Now that I had to think about things and try to fill them out without looking, it became more like 'if I wanted to find this, what would be logical to include in the equation? Yes, it has to be acceleration over time. Now I know better how to use it.

Five students reported following the retrieval practice-advice and these students were almost invariably the same students that contributed to the positive themes above. Seven students reported ignoring the retrieval practice-advice and these students were almost invariably the same students that contributed to the negative themes below.

Six students complained that their lack of understanding of the principles made retrieval practice unhelpful and that it forced them to do rote rehearsal, i.e. repeating the words or symbols without using meaningful connections. One student said, "Then it was just memorization of it. So just looking at it without any sense of purpose or meaning, just try to remember it from session to session."

Four students thought that retrieval practice had limited or low value for learning. Two students thought it was outright ineffective, while two students thought the benefits were short-lived, with one student saying "It is a work you have to continue. If not, you lose the value of it pretty fast, unfortunately."

2. Alignment with theory

Five students seemed to have gained knowledge that accords well with the theory of why one should do retrieval practice. Interestingly, four out of the five students who noticed the intended benefits of retrieval practice were also students who engaged in physics modeling during problem-solving and three of these students also contributed to the themes of *unintentionally using elaborative encoding during self-study* and that *elaborating on connections helps retrieval practice*, the latter being an indication of knowledge of how to do retrieval practice. Although we have to be careful about generalizing quantitative effects with so few students, this clustering of themes accords well with our theoretical expectations that elaborative encoding creates intra- and inter-item associative links, which again stimulates memory reconstruction and potentiates retrieval practice, which again helps with physics modeling. These students were also largely the same students that followed the retrieval practice-advice.

3. Barriers and facilitating aspects

The most important barrier seems to be that students feel their lack of understanding of the symbols in the principles forces them into rote rehearsal during retrieval practice and that this is unhelpful.

The same students ignored the retrieval practice-advice and some of them indicated that retrieval practice had low value. Taking into account that these students did not contribute to the themes of *unintentionally using elaborative encoding during self-study* and *Elaborating connections helps retrieval practice* and that everyone ignored the elaborative encoding-questions, the root cause of these problems seems to be that these students lack meaningful associative links within and between principles. They apparently failed to connect elaborative encoding to retrieval practice and they failed to understand how retrieval practice may help them understand the principles. Despite their apparent misunderstandings, this is something we need to address to realize the full potential of these learning strategies.

4. Discussion of future practice

The themes of *finding retrieval practice increasingly beneficial* and *finding it enjoyable and motivating* indicate that an important way to facilitate retrieval practice is to ensure that students get sufficient practice with the strategy. It is especially encouraging that some students noticed subtle benefits of retrieval practice. However, it is probably hard to ensure that most students use retrieval practice without using highly structured tasks such as what we used in the first few weeks before the Covid-19 shutdown, incorporating retrieval practice as part of the lectures. Therefore, we suggest that structured retrieval practice during lectures is a way to facilitate students' widespread adoption.

The best way to overcome the barriers to effective use of retrieval practice is probably to ensure quality elaborative encoding by all the students. When quality elaborative encoding has been ensured, we must also ensure that everyone gets adequate practice with retrieval practice. A forceful way to ensure this is to implement a mandatory retrieval test. This test can be performed on the same retrieval sheet as the retrieval practice towards the end of the semester, where students have to reach a certain criterion, e.g. 70% correct, to be allowed to take the final exam. This is well within reach for all students and provides them with incentives and clear goals. Ideally, we would want students' practice to be intrinsically motivated. However, we believe this intrinsic motivation will come when they see progress and notice the benefits, in line with our thematic analysis and the results of Abel and Bauml [83].

C. Self-explanation

Table III – Themes from students' experiences and reflections on self-explanation (SE)

Themes in students' experiences and reflections	Connection to research questions 2 and 3
1. Unaware that SE is a learning strategy	Lacking knowledge of what it is
2. Low perceived value of SE	Lacking knowledge of why one should do it
3. Choose to do other things when stuck	Lacking knowledge of when one should do it
4. Did not understand the method	Lacking knowledge of how one should do it & barriers regarding task structure and resources
5. Prefer an intuitive approach to studying solutions	Barriers regarding task structure and resources
6. Self-explanation is very costly	Barriers regarding task structure and resources
7. Likes discussing solutions in social situations	Facilitating aspect

1. Themes in students' experiences and reflections with self-explanation

Three students seemed unaware that self-explaining solutions could be considered a learning strategy. When asked about whether she ever tried to explain a solution to a problem to herself, one student said, "No, I do not. I have actually never done that, so I do not really know if it would work."

Four students expressed doubt in the value of self-explanation, specifically that they perceived low benefit and need for self-explanation, particularly for problem-solutions they found easy to understand.

A reoccurring theme was that students chose to do other things than self-explaining when stuck in problem-solving. Most students said they would rather try to solve the problem and, when stuck, rather use the solution to find minor hints to help them continue with problem-solving. Three students chose to read the textbook or watch digital lectures when stuck. When asked about what she did when stuck on a problem, one student said, "I try to read more, until my face turns green." Four students reported that they could not be bothered with self-explaining solutions. Finally, two students said that studying solutions was their very last resort when stuck. One student said, "It [studying solutions] is the very last resort" and another said, "The solution is often available. But I use it as a 'last resource', you could say". The one clear exception was a student who said he used self-explanations because it was essential to transfer the knowledge to other problems.

Five students expressed difficulty with understanding the method for self-explanations. One student said about the written self-explanation problems from the seminars:

> Many failed to understand this sheet. We sat and wrote those self-explanations during the seminars. And then there was this thing that we should not use numbers, and then there were some who only wrote the procedures, some who only tried to write in words what happened. Yes. It was a bit… I think it was a bit unclear.

Seemingly related to the theme of not understanding the method, six students preferred a more intuitive approach to studying solutions. They talked about how they "tried to understand the steps" and "thought through the solution". Three students also felt that the taught method for self-explanations was too structured and detailed.

Seven students found self-explanation very costly in terms of the effort and time required, saying e.g. "I remember that it is not the easiest thing to explain with words what goes on step-by-step, it is much easier to actually describe what you do with math", "It feels effortful to explain a solution to a problem you have not solved yourself", and "Especially now before the exam I think it takes too much time, really".

Finally, six students said they liked to discuss solutions in social situations. Three students said they liked to discuss solutions in peer groups and three other students said they liked the structured self-explanation practice in the seminars.

2. Alignment with theory

The students apparently have a pervasive lack of metacognitive knowledge of self-explanations, with one exception being the student who said that self-explanation is essential for transfer. When they are unable to solve problems, several students use something similar to what Renkl [70] calls anticipative reasoning, which is to look for some hint in the solution to help them solve the problem on their own. This is a good strategy, especially for skill acquisition, but it is probably less effective than self-explanation for learning the conceptual knowledge needed for physics modeling. One student said that he searched for similar examples and tried to analogically map the solution, which is also a reasonably good strategy for skill acquisition [84]. The most concerning finding was that several students chose to read the textbook or watch video lectures when they were stuck on problems, both very inefficient strategies for learning to solve problems due to the low specificity [11, 85]. This shows a lack of knowledge of when they should self-explain, namely when they are unable to solve the problem with current knowledge.

3. Barriers and facilitating aspects

A large barrier to overcome is students' lack of knowledge of what self-explanation is, and when, why, and how to do it. There seems to be a pervasive view that it is "wrong" or ineffective to study the solutions to problems. This view is implicit in many students' choices and more explicit in that some students view it as a last resort. Several students said they preferred solving problems to explaining solutions, which is good if they have adequate prior knowledge and skill. However, the two are not mutually exclusive and there is a lot of research on how self-explanation is more effective than problem-solving in the early phases of learning to solve problems [86, 87].

Another major barrier is that students find self-explanation very costly in terms of time and effort. This may also be a reason why they prefer using a more intuitive approach to self-explaining solutions.

A potential facilitating aspect was that several students expressed that they liked to discuss solutions to problems with peers.

4. Discussion of future practice

The easiest way to make students aware of self-explanations, and to impart knowledge of when, why, and how to use it, is to hand out a short pamphlet on what self-explanation is, and when, why, and how to do it. Although this method only helps the interested students, it can reduce the time needed for instruction on metacognitive knowledge during lectures and reduce antagonism due to time spent on extracurricular instruction in metacognitive knowledge of learning strategies. The low perceived value of self-explanations seemed tied to low problem difficulty. Hence, the perceived value of self-explanations may increase for more complex problems.

To reduce the cost associated with self-explanations during self-study, we suggest embedding self-explanation in social learning activities, e.g. by using peer instruction of physics models for complex problems. This requires well-thought-out conceptual problems that stimulate high-quality explanation activity. One student said about the peer instruction that "I feel that I learn something, but at the same time I don't feel like I work-work with it. I feel like I learn without working." Embedding self-explanation in social learning tasks, especially if mandatory, can potentially remove the need for self-regulation, bypassing students' implicit beliefs about studying solutions. It might also be a more natural way to learn and internalize how to self-explain. Moreover, it may provide students with social support and both peer feedback and instructor feedback on their explanation-quality. To reduce the required effort associated with self-explaining, we may also need to improve the students' early acquisition of domain knowledge. We believe that this is best done by ensuring a high-quality implementation of elaborative encoding and retrieval practice and by ensuring high participation in both.

D. The solution structure and physics modeling

Getting students to adopt the practice of physics modeling is an overarching goal of our research activities. Therefore, we analyzed students' experiences and reflections regarding the solution structure tool and physics modeling. We identified several facilitators and one main barrier to students' use of physics modeling during problem-solving, see Table IV. We do not discuss alignment with theory, as we did not have specific research questions for the solution structure and physics modeling.

Table IV – Themes from students' experiences and reflections on the solutions structure and physics modeling

Themes in students' experiences and reflections	Connection to research goal
1. Coding and drawing diagrams are prior habits	Neutral
2. New awareness and practice through exposure to physics modeling	Facilitating aspect
3. Gradually persuaded by the benefits of physics modeling	Facilitating aspect
4. Use HPSM as a tool for physics modeling	Facilitating aspect
5. Just trying to solve problems	Barrier
6. Only reflect when problems are difficult or surprising	Neutral

1. Themes in students' experiences and reflections with the solution structure and physics modeling

It seems that most students had pre-existing problem-solving habits that included some form of coding and drawing a diagram. However, we noticed that some students had adopted our terminology relating to coding, specifically "coding", "goal variables", and "given variables".

Most students mentioned how physics modeling and the focus on principles' conditions of application were new to them, while the rest of the problem-solution structure was similar to what they had learned in high-school or what they already did. When asked whether his use of the structure was old habits from high-school, one student said:

> We were told [at high-school] to set up what we have, what we wanted to find, and then draw a diagram. Then you have sorted the data from the text. That helps a lot. It is the [physics] model that is 'new'.

The same students also reported that they went to the seminars mainly to learn how to structure solutions and that they tried to follow the solution structure in their own problem-solving. Two students also said that they had started purposefully looking for the conditions of application for new principles they encountered. Five students reported gradually adopting physics modeling after seeing its benefits. Two students also contrasted these benefits with the problems they experienced when *just trying to solve* the problems. Three students apparently used the Hierarchical Principle Structure for Mechanics as a tool for finding physics principles during physics modeling.

The main negative finding from our analysis was that some students were *just trying to solve problems*. These students had high-school habits that they were happy with, seeing no reason to learn a new way to solve problems; they viewed physics principles as "formulas"; they were satisfied with getting the correct answer and saw no reason for reflecting on the solution; and they believed physics modeling was something you did on exams. Finally, students only reflect on the solutions when the problem was perceived as difficult or surprising and some students report never reflecting on a solved problem.

2. Barriers and facilitating aspects for physics modeling

The main barrier to physics modeling seems to be the poor problem-solving habit of just trying to solve problems. We believe that what worked for the students who adopted physics modeling—exposure and increased awareness of physics modeling and its benefits—will also work for students who just try to solve problems. The solvers may be late adopters who will eventually be persuaded by a critical mass of modelers.

It seems that exposure to the idea of physics modeling through the seminar and seminar problems was enough to persuade a large proportion of the students to adopt the practice. Most students tried to follow the structure or said they already did most of it, while about half the students had also adopted the practice of physics modeling. Physics modeling—with its focus on physics principles and their conditions of application—seems to be a new feature of problem-solving for the students, as evidenced by several students mentioning how it was a new feature and no one mentioning already doing it. It also seems to be relatively simple to get an idea of how to do physics modeling, as it seems to be enough to have someone model the process or even to merely see it clearly separated and named in problem-solutions. The Hierarchical Principle Structure for Mechanics also seems to be a useful tool when trying to model problems. Our findings also indicate that when students try the practice of physics modeling, they notice the benefits and gradually adopt it in favor of just trying to solve problems. We find these results encouraging as it seems relatively easy to get students to consciously adopt physics modeling in their problem-solving.

3. Discussion of future practice

Our first suggestion is to clearly separate the structural elements of a large proportion of the solutions students are exposed to, especially separating the physics modeling from the mathematical procedures. It is a relatively easy practice to implement, for example by uploading solutions to weekly problems, and it has a high potential gain. Our experience tells us that the solution structure is more convincing for complex problems that require at least two equations to be solved. Too simple problems and problems that are broken-into-parts can remove the need for physics modeling [88], rather stimulating formula-hunting. Therefore, the most beneficial problems are those that involve multiple equations, especially synthesis problems that span multiple principles [6, 89]. Indeed, Antonenko, Ogilvie [19] found that more complex problems, requiring multiple principles for their solution, was effective for gradually changing some students' habits towards a more physics modeling-based approach.

Our second suggestion is to give the same type of solutions to seminar and workshop leaders and to instruct them in the practice and rationale of physics modeling.

E. The Hierarchical Principle Structure for Mechanics

The Hierarchical Principles Structure for Mechanics (HPSM) is a central tool in the integration of the three learning strategies, as it is useful for every learning strategy. Therefore, we did a separate explorative analysis of the students' experiences and reflections, see Table V. The conclusion is that the hierarchical principle structure seamlessly integrated with students' study habits, both old and new. We do not discuss alignment with theory or barriers and facilitators, as there is no established theory, there were no major barriers, and there seems to be no need for facilitators.

Table V – Themes from students' experiences and reflections on the Hierarchical Principle Structure for Mechanics (HPSM)

Themes in students' experiences and reflections	Evidence of seamless integration
1. Use HPSM for problem-solving	Positive
2. Use HPSM during lectures and reading	Positive
3. Use HPSM for checking units and concepts	Positive
4. HPSM is always nearby	Positive
5. High perceived usefulness	Positive
6. Want minor modifications in HPSM	Implicitly positive
7. Use HPSM sparingly	Neutral

1. Themes in students' experiences and reflections with the Hierarchical Principle Structure for Mechanics

Most students reported using the Hierarchical Principle Structure for Mechanics (HPSM) during problem-solving, which they did in three different ways: They remembered equations from HPSM due to prior use and retrieval practice; they looked up the equations when they failed to remember; and they searched for equations when they were stuck on a problem. We know from the findings in section D that some students are *just trying to solve the problems* while other students were trying to do physics modeling. The same students tended to call HPSM the 'formula sheet' and the 'principle structure', respectively.

Five students reported that they used HPSM during lectures and reading. They used it during peer instruction to check their intuition and to support their arguments. They used the backside of HPSM to check the units and what concepts the symbols were for. Finally, several students reported always having HPSM nearby. Two students actually showed the interviewer where they had hung it up on the wall.

The students' high perceived usefulness for HPSM was a strong piece of evidence for seamless integration. Two students reported that it made it easier to see the deep structure in the course and four students said it gave them a better overview of the course. One student said:

> It is with me always. Because it's so nice. I think it's very well structured, like: Ok, this, this, and then you see that 'Ok, a lot of the things are repeated.' For you can see things in parallel: Ok, but this is the same' and then… Yes, it's just ingenious. It's very nice to see that: 'This is what we are going to learn.'

Finally, more than half of the students spontaneously praised the HPSM, saying things like "It is the most beautiful sheet of paper in the world.", "I think everyone loves it", and "It has been very useful, very useful."

We interpret the students' requests for minor modifications of HPSM as implicit evidence that HPSM was well integrated into their study. Two students said they wanted some things on the HPSM that was not there and two students didn't like that some symbols and subscripts were different from what they were used to.

Three of the students reported not using HPSM that much, with two of them citing as a reason that they did their own compilation of "formulas". However, both of these students switched to HPSM when their notes became too voluminous, with one of them saying:

> But I think it is very nice now, when I am starting to know the course, to recognize them and just throw a glance at the sheet and find the formulas I need instead of having to flip through seven different documents on the PC to find just the formula I needed.

The third student said that he used the book during problem-solving, but he also reported stopping with problem-solving early in the semester because he planned to retake the exam over the summer. Further, he said, "But the sheet is definitely useful, so its use should be continued."

Lastly, one student reported one of the main benefits we were hoping for with the Hierarchical Principle Structure for Mechanics:

> …after you have used it that many times, that sheet, it makes… The formula sheet, it is somehow saved in your head. So, in the end, I didn't need to use it, because I knew them all.

2. Discussion of future practice

We suggest that instructors in mechanics provide students with the Hierarchical Principle Structure for Mechanics [10] or a similar hierarchical principle structure. It seems that the Hierarchical Principle Structure for Mechanics seamlessly integrates with the students' study habits and that almost everyone chooses to use it. They use it for problem-solving, they use it for other study strategies, and it helps them get an overview and to see structural similarities between the different parts of the course. The second author integrated the hierarchical principle structure into her lectures, gradually revealing parts of it as she introduced new principles. A lecturer can also advise students to use it to construct arguments during peer instruction or to use it as a starting point for discussion. In conclusion, the Hierarchical Principle Structure for Mechanics is a useful tool that can be adapted for use in any learning activity where physics principles are the core ideas.

IV. GENERAL DISCUSSION AND CONCLUSIONS

A. Do the findings agree with prior findings?

The results agree with the literature in that it is difficult to get students to adopt learning strategies and that students tend to have poor metacognitive knowledge of learning strategies. We identified some of the same themes as Biwer, Egbrink [36], namely students' uncertainties about effort and time management and the lack of knowledge of how to implement the learning strategies. Our results also agree with others in that students lack the required self-regulation and that they need support [90]. Our findings generally support the findings of Yan, Bjork [30], in that the students' sense of effort with the learning strategies, pre-existing beliefs about learning, and thoughts about learning styles were barriers to their use of effective learning strategies. Renkl, Solymosi [91] discussed three potential reasons why students chose not to use self-explanations after their short-term training intervention: low perceived usefulness, low saliency of strategy during self-study, and too short intervention. Our findings also indicate low perceived usefulness as a barrier. However, we feel that the main barrier is the high cost of engaging in self-explanations, with the second-largest barrier being the faulty beliefs about learning implicit in their choosing to do other things.

B. Implications for further integration of learning strategies

The encoding strategies—elaborative encoding and self-explanation—appear to be especially effortful and difficult to understand. The task structure of both these strategies seems to be opaque to the students. In section III, A and C, we suggested that these strategies should be embedded in social learning tasks, perhaps mandatory in the case of elaborative encoding. Social learning processes can remove the mental effort barrier and capitalize on additional scaffolds such as providing students with different roles, immediate feedback, and peer modeling. However, both elaborative encoding and self-explanation require further resource and task structure development for effective integration into physics courses.

We found that retrieval practice is easy to implement and that several students kept doing it after the Covid-19 shutdown. However, we highly doubt that many students would adopt retrieval practice if it was merely encouraged and the required resources made available, even if given direct instruction in the what, when, why, and how. Therefore, we believe that the practice of structured retrieval practice in lectures, or something similar, is crucial for ensuring students' use of this strategy.

Most students adopted the problem-solution structure and some students also adopted the practice of physics modeling. We suspect that more students would adopt physics modeling with well-implemented peer instruction using self-explanation of physics models and with a more holistic integration where the provided problem solutions, the lecturer, and the teaching assistants all focus on physics modeling as an essential part of physics. The Hierarchical Principle Structure for Mechanics is a useful tool for teaching, learning, and doing physics modeling. It can also be useful for elaborative encoding, retrieval practice, and self-explanation, and for many other learning strategies and activities.

Finally, we believe that students would greatly benefit from the integration of learning strategies in multiple courses during the first few semesters of their study program. One semester may not provide enough time and practice to change ingrained habits [25, 36, 92].

C. Strengths and limitations of this study

A thematic analysis does not warrant claims of trends, correlations, or effects. Rather, its strength lies in providing a depth of understanding, providing descriptions of what students' do and think. This provides us researchers with an improved understanding of the processes before testing the effects.

Whether our findings are likely to generalize to the students, treatments, settings, and outcomes relevant to the reader's context is a qualitative judgment that the reader must make [93].

D. Future research

Further research needs to be done to find effective ways to integrate self-explanations and elaborative encoding into physics courses. One potential line of research is to develop instructional material for peer instruction of self-explanations and to analyze and optimize the learning processes. We also need to improve the task structure and instructional resources for elaborative encoding, ensuring that the associative links produced during elaborative encoding potentiates retrieval practice. More research should also be done to identify the intra- and inter-principle associative connections that are most useful for improving students' self-explanation and problem-solving.

V. ACKNOWLEDGEMENTS

This work was supported by the University of Bergen. We would like to thank Robert Gray Jr for his advice on how to structure the interview guide. We would like to thank Matthias Gregor Stadler, Mildrid Kyte, and Vegard Havre Paulsen for valuable discussions of the thematic analysis.

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Supplementary material for:

Gjerde, V., Holst, B., & Kolstø, S. D. Integrating Effective Learning Strategies in Basic Physics Lectures: A thematic analysis.

Contents

Tool 1: Elaborative Encoding-Questions

Table I - Elaborative encoding-questions. These can also be seen in Norwegian on the back of HPSM. The bolded questions were visible on a projector screen during the retrieval sessions, adjacent to the retrieval practice-advice. Adapted from [1].

Questions for Elaborative Encoding
Detail-level
1. **What concepts and SI-units belong to the symbols in the principle?**
2. What do these concepts mean to you?
Principle-level
3. **What is the principle called? Any thoughts on why?**
4. **What are the conditions of application for the principle?**
5. Why is that a condition for the principle?
6. **What happens if one variable in the principle changes size?**
Hierarchy-level
7. **What is the row name and column name it is placed in?**
8. **What similarities and dissimilarities do you see with other principles in HPSM?**
9. Is it empirically derived or is it deductively derived from other principles in HPSM?

Example Q&A for the elaborative encoding-questions

Table II - One of the five example Q&As that we uploaded.

Elaborative Encoding of Conservation of linear momentum – Q&A

4

Conservation of linear momentum

Condition: **Conservation:**

$$\sum \boldsymbol{F}_{sys} = \frac{d\boldsymbol{p}_{sys}}{dt} = 0 \longrightarrow \boldsymbol{P}_i = \boldsymbol{P}_f$$

It is not expected of you to be able to answer all the questions in the same way as what is done under. What is important is that you try to answer the questions for many principles, multiple times, throughout the semester.

Detail-level

(for new symbols and concepts)

1. **What concepts and SI-units belong to the symbols in the principle?**

Conservation of linear momentum consists of forces, with the unit Newton [kgm/s^2], time with the unit seconds [s], and momentum with the unit kilogram meter per second [kgm/s]. Subscript 'sys' stands for system, 'i' stands for initial, and 'f' for final.

2. **What do these concepts mean to you?**

Forces are behind all processes in nature. A force can be defined, by Newton's second law, as that which accelerates an object with mass m. Linear momentum is a vector, unlike kinetic energy, and is defined as mass multiplied with velocity. The magnitude of the linear momentum is relative to a coordinate system, and can only be changed by external forces acting on the given system.

Principle-level

3. **What is the principle called? Any thoughts on why?**

The principle is called Conservation of linear momentum, which accurately describes the principle.

4. **What are the conditions of application for the principle?**

The condition for conservation of linear momentum is that the sum of external forces on the system is equal to zero.

5. **Why is that a condition for the principle?**

The condition comes directly from Newtons second law, which states that if the net forces on the system is zero the acceleration is also zero, where mass multiplied with acceleration can be written as change in momentum per time and, therefore, change in momentum is zero. The reason for clarifying that we are talking about external forces is that the internal forces can always be summed to zero, by Newtons third law. For example, in a system with two planets, the gravitational force planet 1 exerts on planet 2 must be exactly the same size and in the opposite direction as the gravitational force from planet 2 on planet 1. The same applies to all other forces between all objects in the system.

6. **What happens if one variable in the principle changes size?**

If the condition of application for the principle is met, the linear momentum in the final state must be increases if the linear momentum in the initial state is increases, and vice versa. In other words, they must be the same. If the sum of the external forces on the system is different from zero, we have an impulse on the system, where the size of the impulse is determined by the duration and size of the net external force, and the linear momentum changes. Then, we must use the Impulse-Momentum Theorem.

Hierarchy-level

7. **What is the row name and column name it is placed in?**

Conservation of linear momentum is placed in the translational mechanics row and the momentum column.

8. **What similarities and dissimilarities do you see with other principles in HPSM?**

You could say that conservation of linear momentum is a special case of the impulse-momentum theorem with the net force equal to zero. You could also say that the Impulse-momentum theorem is really Newtons second law, where the net force is equal to mass times change in velocity per time (acceleration). In other words, conservation of linear momentum describes a system where the net external force is zero and the Impulse-momentum theorem describes a system where the net external force is different from zero. We can also see that the principle is completely analogue to conservation of angular momentum, where the net external torque is analogue to the new force and angular momentum is analogue to linear momentum.

9. **Is it empirically derived or is it deductively derived from other principles in HPSM?**
   (This is a difficult question in many cases and is not necessary for doing well in the course. The question is meant for those who want to go deep into physics, but the answers are valuable to everyone.)

Conservation of linear momentum can be derived from Newtons second law, where acceleration is zero (Newtons first law).

Tool 2: The Hierarchical Principle Structure for Mechanics, with the associated retrieval sheet and retrieval practice advice

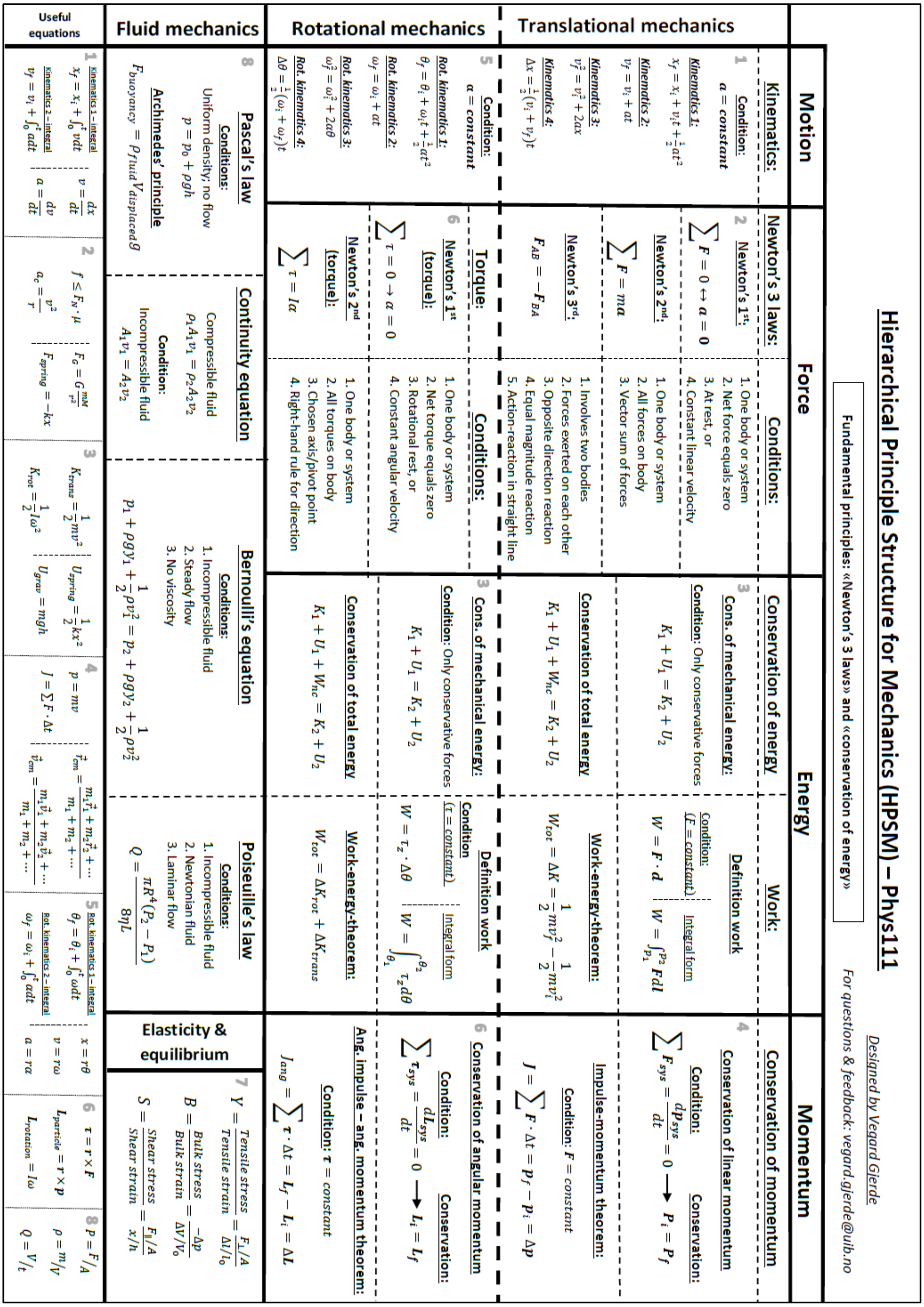


Figure 1 – The Hierarchical Principle Structure for Mechanics [1], the front side.

Symbol	Name	SI Units
t:	Time	s
x:	Distance	m
v:	Velocity/speed	m/s
a:	Acceleration	m/s^2
F:	Force	$N = Newton = kg\, m/s^2$
k:	Spring constant	N/m
$\boldsymbol{\mu}$:	Coefficient of friction	NA
f:	Frictional force	N
$\boldsymbol{a_c}$:	Centripetal acceleration	m/s^2
$\boldsymbol{G}$:	Gravitational constant	$6.67 * 10^{-11}\, m^3 kg^{-1} s^{-2}$
K:	Kinetic energy	$J = Joule = kg\, m^2/s^2$
U:	Potential energy	J
W:	Work	J
$\boldsymbol{W_{nc}}$:	Work by non-conservative forces	J
d:	Distance	m
P:	Total linear momentum	$kg\, m/s$
p:	Momentum of object	$kg\, m/s$
J:	Impulse	$kg\, m/s$
$\boldsymbol{\theta}$:	Angle/Angular displacement	rad
$\boldsymbol{\omega}$:	Angular speed/frequency	rad/s
$\boldsymbol{\alpha}$:	Angular acceleration	rad/s^2
$\boldsymbol{\tau}$:	Torque	$kg\, m^2/s^2$
I:	Moment of inertia	$kg * m^2$
L:	Angular momentum	$kg\, m^2/s$
ρ:	Density	$kg * m^{-3}$
p:	Pressure	$Pa = Pascal$
η:	Viscosity	$Pa * s$
Y:	Young's modulus	Pa
B:	Bulk modulus	Pa
S:	Shear modulus	Pa

Spørsmål for Elaborative Encoding (EE)

Tenk på og diskuter disse spørsmålene for å utvikle forståelsen av hvert prinsipp og definisjon i HPSM.

For hvert prinsipp (og definisjon):

Detaljnivå

1. Hvilke begrep og SI-enheter tilhører symbolene i prinsippet?
2. Hva betyr disse begrepene for deg? (nye begreper)

Prinsippnivå

3. Hva heter prinsippet? Har du tanker om hvorfor?
4. Hva er betingelsen(e) for prinsippet?
5. Hvorfor er det en betingelse for det prinsippet?
6. Hva skjer hvis én variabel i prinsippet endrer størrelse?

Hierarkinivå

7. Hva er navnet på rekken (og kolonnen) det er plassert i?
8. Hvilke likheter og ulikheter ser du med andre prinsipper i HPSM?
9. Er det empirisk eller kan det utledes fra andre prinsipper i HPSM? Hvordan?

Figure 2 – The Hierarchical Principle Structure for Mechanics [1], the back side.

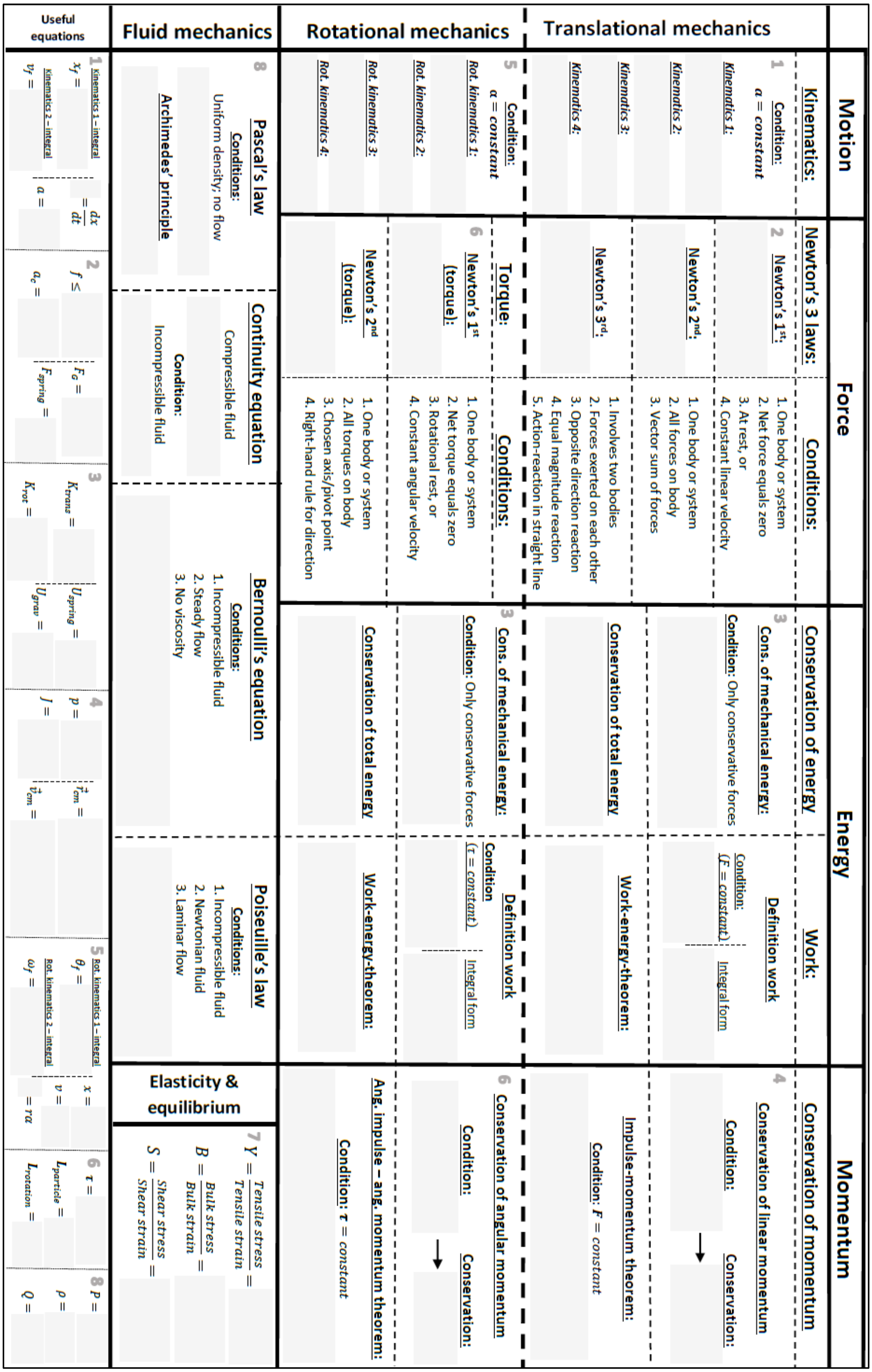


Figure 3 – The retrieval sheets. The back side was identical. Adapted from [1].

Table III - Retrieval practice advice as presented on a projector screen during the retrieval practice sessions. The elaborative encoding-questions were shown adjacently. Adapted from [1].

Advice for Retrieval Practice *(Purpose: Maximize memory strength)*
1. First, fill in as much as you can remember. (If you have remembered a whole box in HPSM at least four sessions in a row and you feel it sticks, you can skip it this session and rather put a checkmark in that box) 2. Retrieval is most effective when the retrieval attempt is successful; restudy is most effective after retrieval failure. 3. When you go 15-30 seconds without remembering more: a. Restudy and retrieve old memories mentally b. Write down the mentally retrieved memories c. Repeat step a & b until all the old memories are retrieved 4. Use elaborative encoding on one new HPSM-box at the time, and: a. Write down what you remember b. Do mental retrieval plus feedback on the rest until they stick c. Write down what you did not remember in step a 5. Make time for retrieval repetition of new memories on the backside [of the retrieval sheets]

Tool 3: The solution structure

11.9**

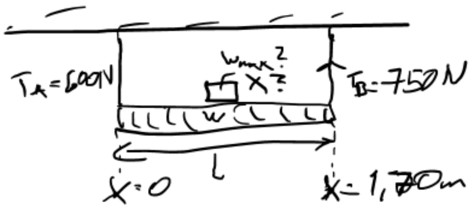
A uniform, 400-N, 1.70-m bar is suspended horizontally by two vertical cables at the ends. Cable A can support a maximum tension of 600 N, and cable B can a maximum tension of 750 N. You place a small weight on the bar. (a) How much weight can you put on the bar without breaking a cable, and (b) where is the best place to put the weight?

1. Coding

Goal: w_{max}, x

Given: w, l, T_A, T_B

2. Diagram



3. Physics Model

1. $\sum F_y = T_A + T_B - w - w_{max} = 0$
2. $\sum \tau_A = lT_B - \frac{l}{2}w - xw_{max} = 0$

4. Mathematical Procedures

1. $w_{max} = T_A + T_B - w$
2. $w_{max} = 600N + 750N - 400N$
3. $w_{max} = \underline{950N}$
4. $xw_{max} = lT_B - \frac{l}{2}w$
5. $x = \frac{lT_B - \frac{l}{2}w}{w_{max}}$
6. $x = \frac{1.70m * 750N - \frac{1.70m}{2} * 400N}{950N}$
7. $x = \underline{0.984m}$

5. Reflection

(discussed in seminar)

Figure 4 - Example of the five-step problem-solution structure as presented in the uploaded solutions.

Principle 1 (condition): Newtons' 1. ($a = 0$)
Principle 2 (condition): Newtons' 1. for rotation ($\alpha = 0$)

Figure 5 - The principles and their conditions of application were explicated at the end of the uploaded solution document for all the problems in the problem set

Original quotes and the English Translation

"Det blir så mye for så lite, synes jeg."

"It is so much for so little, I think"

"Det er vel mest at jeg personlig ikke har følt så stort behov for det. Og kanskje litt at jeg ikke har giddet å bruke tid på det, på en måte."

"I guess it is because I haven't felt a need for it. And maybe that I couldn't bother spending time on it, in a way".

"Fordi jeg tror det kommer mer ut av det at jeg tar det heller ut av selve prinsippet i stedet. [...] Jeg tror kanskje jeg bruker mer fysisk symbolene i formelen, eller prinsippet, for å huske hva den egentlig sier og hvordan den ser ut. I stedet for nødvendigvis å gå bak og se: «Ok, denne formelen gir joule, dette er da sånn og sånn og sånn.» Jeg tror det går mer der."

"I think it comes more out of the principle. […] I think I rather use the physical symbols in the formula, or principle, to remember what it really says and how it looks. Instead of going back and looking [at the elaborative encoding-questions], 'Ok, this equation gives joule, this is then this and this and this.' I think it is more like that."

"...si du kan disse formlene allerede nå, og så kommer du da på forelesning, du har sett formelen før, du blir ikke sånn [gispelyd] med én gang du ser formelen, men «Å ja, det er den og den. Kult, yes, det er den loven.» Og så forklarer de hvorfor det blir sånn, og så bare: «Å, ja. Kult.»"

"Say you know these equations already now, and then you come to a lecture, you've seen the equation before, you don't become like *gasping sound* when you see the equation, but 'oh yeah, that is that and this. Cool, yeah, that is this law.' And then they explain why it's like that, and then just 'oh, yeah. Cool.'"

"Når man sitter hjemme på et lite rom her hele dagen, kan man få dårlig konsentrasjonsevne. Det er vanskelig å starte fordi man vet man skal sitte her så lenge. Så jeg har ofte brukt den som en sånn «Denne tar bare 15 minutter, så den starter du med.»"

"When you sit at home in a little room all day you can struggle with your concentration. It is hard to start because you know you have to sit for a long time. So, I have often used it [retrieval practice] as a 'this only takes 15 minutes, so you start with that' and then I often notice that it is easier to start things. Then I can already put a checkmark that I have done something that day."

"...jeg er egentlig litt dårlig på det. Jeg har aldri gjort det, for jeg synes det er skikkelig kjedelig. Er det insentiv det heter? Det er jo gøy å fylle et ark, uke etter uke, for å se at man kan det. Jeg prøver å bruke det som motivasjon – denne uka fylte jeg ut så mye, neste uke skal jeg fylle ut litt mer. Så blir det jo fullt til slutt."

“I am actually bad at it [memorization]. I have never done it [before], because I think it is really boring. Is it incentive you call it? It is fun to fill out a sheet of paper, week after week, to see if you know it. I try to use it as motivation—this week I filled out this much, next week I will fill out more. Then it becomes full eventually.”

"Nå, som jeg har måttet tenke over ting og prøve fylle dem inn uten å se det, ble det litt mer sånn «Hvis jeg skal finne ut det, hva er det som er logisk at er med i den ligningen? Jo, da må det være akselerasjon over tid.». Nå vet jeg mer nøyaktig hvorfor jeg skal bruke den."

“Now that I had to think about things and try to fill them out without looking, it became more like ‘if I wanted to find this, what would be logical to include in the equation? Yes, it has to be acceleration over time. Now I know better how to use it.”

"Da var det bare memorisering av den. Så å bare se på den uten noen særlig mål og mening, bare prøve å huske den fra gang til gang."

“Then it was just memorization of it. So just looking at it without any sense of purpose or meaning, just try to remember it from session to session.”

"Det er et arbeid man må gjøre kontinuerlig, hvis ikke mister man verdien av det ganske fort, dessverre."

“It is a work you have to continue. If not, you lose the value of it pretty fast, unfortunately.”

"Nei, det gjør jeg ikke. Det har jeg faktisk aldri opplevd, så jeg vet egentlig ikke om det hadde funket."

“No, I do not. I have actually never done that, so I do not really know if it would work.”

"Da prøver jeg å lese litt mer, til jeg blir helt grønn i ansiktet."

“I try to read more, until my face turns green.”

"Det er aller siste utvei"

“It [studying solutions] is the very last resort”

“Ofte er det jo et løsningsforslag. Men det velger jeg å bruke som en «last resource», kan du si.»

“The solution is often available. But I use it as a ‘last resource’, you could say”.

"Det her arket tror jeg det var veldig mange som ikke helt forstod. Vi satt og skrev de selvforklaringene på oppgavegjennomgangen. Og så var det vel at vi helst ikke skulle bruke tall, og så var det noen som bare skrev regnestykker, noen prøvde å bare skrive med ord hva som skjedde. Ja. Det var litt … Jeg tror det var litt uklart. "

“Many failed to understand this sheet. We sat and wrote those self-explanations during the seminars. And then there was this thing that we should not use numbers, and then there were some who only wrote the procedures, some who only tried to write in words what happened. Yes. It was a bit… I think it was a bit unclear.”

"Jeg husker at det er ikke det letteste å bare forklare med ord hva som foregår steg for steg, det er mye lettere å faktisk beskrive hva du gjør med matte."

“I remember that it is not the easiest thing to explain with words what goes on step-by-step, it is much easier to actually describe what you do with math”,

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"Det føles også litt arbeidsomt å skulle forklare en oppgave man ikke har løst selv."

“It feels effortful to explain a solution to a problem you have not solved yourself”

"Spesielt nå før eksamen så synes jeg det tar litt for mye tid, egentlig, selv om det kanskje er fort gjort òg"

“Especially now before the exam I think it takes too much time, really”.

"Ja, det var det vi fikk fortalt på videregående. Vi ble anbefalt å sette opp det man har, det man skal ha og så tegne en tegning. Da har du sortert dataen ut ifra teksten. Det hjelper jo mye på. Det er jo den modellen som er «ny»."

“We were told [at high-school] to set up what we have, what we wanted to find, and then draw a diagram. Then you have sorted the data from the text. That helps a lot. It is the [physics] model that is new.”

"Det er med, alltid. For den er så fin. Jeg synes det er veldig bra strukturert, sånn: Ok, sånn, sånn, og så ser du at «Ok, veldig mye ting går igjen.» For du kan liksom se ting parallelt: «Ok, men det er det samme.» Og så … Ja, den er bare helt genial. Veldig deilig å se bare: «Dette er det vi skal lære.»"

“It is with me always. Because it’s so nice. I think it’s very well structured, like: Ok, this, this, and then you see that ‘Ok, a lot of the things are repeated.’ For you can see things in parallel: Ok, but this is the same’ and then… Yes, it’s just ingenious. It’s very nice to see that: ‘This is what we are going to learn.’”

“Det er det flotteste arket i hele verden."

“It is the most beautiful sheet of paper in the world.”

“Den tror jeg alle elsker."

“I think everyone loves it”

“Det har vært veldig nyttig, veldig nyttig."

“It has been very useful, very useful.”

"Men jeg synes det er veldig greit nå, når jeg begynner å kunne faget godt, og kjenne dem igjen og bare kaste et blikk på arket og finne formlene jeg trenger framfor å bla gjennom syv ulike dokumenter på PC-en for å finne akkurat den formelen jeg trengte. "

“But I think it is very nice now, when I am starting to know the course, to recognize them and just throw a glance at the sheet and find the formulas I need instead of having to flip through seven different documents on the PC to find just the formula I needed.”

"Ja, for etter du har brukt det såpass mange ganger, det arket, så lager det … Det formelarket det lagres liksom i hodet ditt. Så til slutt trengte jeg ikke å bruke det, fordi jeg kunne alle.»

“…after you have used it that many times, that sheet, it makes… The formula sheet, it is somehow saved in your head. So, in the end, I didn’t need to use it, because I knew them all.”

Interview guide

We have omitted some questions that were only related to digital teaching after the Covid-19 shutdown.

Starting the interview

- Interviewer introducing himself
- Turning on presentation slides with contextual material, see Table IV – The content of the slides for contextualizing the questions
- Asking for permission to turn on the camera
- Starting:

Table IV – The content of the slides for contextualizing the questions

- **Part 1 – Lectures**
  - Slide from traditional lecture
  - Peer Instruction conceptual problem
- **Part 2 – Problem-solving and self-explanation**
  - Slide of problem-solution from the problem-solving seminar
  - Written self-explanation worksheet
  - Problem sheet for problem-solving seminars
  - A solution from the problem-solving seminar (using the solution structure)
- **Part 3 – HPSM, retrieval practice, and elaborative encoding**
  - The Hierarchical Principle Structure for Mechanics
  - Retrieval practice sheets
  - Retrieval practice advice
  - Elaborative encoding-questions
  - Sample elaborative encoding answers
  - Announcement advising use of elaborative encoding

Part 1 – Lectures

1. How often did you attend lectures before the Covid-19 shutdown?
    a. What are your reasons for attending lectures?
    b. What did you do in the lectures to maximize your learning?
        i. Probing questions on how, if needed
2. To what extent did you attend the peer instruction sessions before the Covid-19 shutdown?
    a. What did you do during the different phases of peer instruction?
        i. Probing questions on how, why, and reflections on benefits and drawbacks

Part 2 – Problem-solving and self-explanation

3. Do you solve many problems when you study for the exam in this course?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
4. What would you say is your approach when you try to solve problems in this course?
    a. Probing questions on how/problem-solving strategies and repairing strategies when stuck

5. [The seminar leader] used a certain structure for solving problems, with coding, diagrams, physics model, and procedures in the problem-solving seminars: Do you try to do something similar when you solve problems?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
6. Have you attended the problem-solving seminars?
    a. Why do you choose to (not) attend the problem-solving seminars?
    b. How do you use the problem-solving seminars?
        i. Probing questions on how, why, and reflections on benefits and drawbacks
7. Three weekly self-explanation problems have been uploaded each week. To what extent have you used these?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
8. [The seminar leader] has also tried to teach the students how to self-explain worked examples to maximize learning, by focusing on the principles, conditions, and how to set up the physics model, and the goals of the mathematical procedures: Do you try to explain to yourself in this way when you study solutions?
    a. Probing questions on how, why, and reflections on benefits and drawbacks

<u>Part 3 – HPSM, retrieval practice, and elaborative encoding</u>

9. What do you call this sheet? *[shows slide with the Hierarchical Principle Structure for Mechanics]*
10. To what extent have you used the 'hierarchical principle structure'/'formula sheet'/'principle structure' in your study?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
11. To what extent have you attended the retrieval practice sessions in the lectures before the Covid-19 shutdown?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
12. [The seminar leader] had some advice for how to do retrieval practice. Did you follow this advice during the retrieval practice sessions?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
13. [The seminar leader] has recommended that students try to answer the elaborative encoding-questions during self-study, alone or in groups. Have you ever done that?
    a. Probing questions on how, why, and reflections on benefits and drawbacks
    b. He also uploaded examples of how to answer these elaborative encoding-questions. Have you noticed or used this?

<u>Ending the interview</u>

References

1. Gjerde, V., B. Holst, and S.D. Kolstø, *Retrieval practice of a hierarchical principle structure in university introductory physics: Making stronger students.* Physical Review Physics Education Research, 2020. **16**(1): p. 013103.

Graphic design: Communication Division, UIB / Print: Skipnes Kommunikasjon AS

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ISBN: 9788230854730 (print)
9788230869994 (PDF)