Experiencing Molecular Processes
The Role of Representations for Students’ Conceptual Understanding

Caroline Larsson

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Linköping University, Department of Social and Welfare Studies
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The universe is full of magical things patiently
waiting for our wits to grow sharper

Eden Phillpotts, *A Shadow Passes*, 1919

In this quotation, Phillpotts (1919) refers to the beauty of plants that may lie hidden and can only be seen using a magnifying lens. Most specifically, he is referring to the species *Menyanthes*, which “must have bloomed and passed a million times before there came any to perceive and salute her loveliness”. Phillpotts concludes that there must be many “magical things” that will be discovered as our knowledge grows.
Knowledge of molecular processes is crucial for fundamental understanding of the world and diverse technological applications. However, they cannot be clearly related to any directly experienced phenomena and may be very different from our intuitive expectations. Thus, representations are essential conceptual tools for making molecular processes understandable, but to be truly useful educational tools it is essential to ensure that students grasp the connections between what they represent and the represented phenomena. This challenge and associated personal and social aspects of learning were key themes of my doctoral research.

This thesis evaluates whether (and if so how) representations can support students’ conceptual understanding of molecular processes and thus successfully substitute the missing experience of these processes. The subject matter used to explore these issues included two crucial molecular processes in biochemical systems: self-assembly and adenosine triphosphate synthesis. The discussion is based on results presented in four appended papers. Both qualitative and quantitative research strategies have been applied, using instruments such as pre- and post-tests, group discussions and interviews. The samples consisted of Swedish and South African university students, who in the group discussions interacted with peers and external representations, including an image, a tangible model and an animation.

The findings indicate that students’ ability to discern relevant model features is critical for their ability to transfer prior conceptual knowledge from related situations. They also show that students’ use of metaphors and conceptual understanding depend on how an external representation conveys relevant aspects of the learning content (its design). Thus, students must manage two complex interpretation processes (interpreting the external representations and...
Abstract

metaphors used), which may create challenges for their learning. Furthermore, the self-assembly process was shown to incorporate counter-intuitive aspects, and both group discussion and the tangible model proved to be important facilitators for changing students’ conceptual understanding of the process. The tangible model provided them with an illuminating experience of the phenomena. In particular, the tangible model had two functions, first as an “eye-opener”, and then as a “thinking tool”, and acted as a facilitator in the group discussions by reducing the student’s conceptual threshold, allowing them to accept the counter-intuitive aspects and integrate relevant elements of their prior knowledge. In addition, providing students with a conflict-based task, problem or representation is not enough, they also have to be willing (emotionally motivated) to solve the conflict.

The challenge for educators lies in choosing representations that convey aspects of the learning content they are intended to teach and assist students in their meaning-making of the representations by remaining informed of students' background knowledge and interpretations. Results presented in this thesis show that it could be advantageous to interpret learning in a broader sense.
Kunskap om molekylära processer är avgörande för att skapa en grundläggande förståelse av världen och olika tekniska tillämpningar. Däremot kan molekylära processer inte alltid relateras till direkt erfarna fenomen och de kan skilja sig mycket från våra intuitiva förväntningar. Således blir representationer viktiga konceptuella verktyg för att göra molekylära processer begripliga. För att representationer skall vara användbara pedagogiska verktyg är det viktigt att eleverna förstår sambanden mellan vad de representerar och de representerade fenomenen. Denna utmaning och tillhörande personliga och sociala aspekter av lärande var centrala teman i mitt doktorsarbete.


Resultaten tyder på att studenternas förmåga att urskilja relevanta aspekter hos en extern representation är avgörande för deras förmåga att överföra tidigare kunskaper från likartade situationer. Resultaten visar också att studenternas metaforiska språk och konceptuella förståelse beror på hur den externa representationen förmedlar relevanta aspekter av lärandeinnehållet (dess design).
Swedish Abstract

Därmed måste studenterna hantera två komplexa tolkningsprocesser (tolka de externa representationer och de metaforer som används), vilket kan skapa utmaningar för lärandet. Dessutom innehöll den molekylära processen self-assembly kontra-intuitiva aspekter och både gruppdiskussionerna och den konkreta modellen visade sig spela en viktig roll för att förändra elevernas konceptuella förståelse av processen. Framför allt hade den konkreta modellen två funktioner, först som en ”ögon-öppnare” och sedan som ett verktyg för studenternas tänkande i gruppdiskussioner genom att minska den konceptuella tröskeln. Erfarenheten av processen gav studenterna möjligheten att acceptera de kontraintuitiva aspekterna och integrera relevanta delar av deras förkunskaper. Att ge studenter en konflikt-baserad uppgift och en representation räcker dock inte, de måste också vara villiga (känslomässigt motiverad) att lösa konflikten.

Utmaningen för lärare ligger i att välja representationer som förmedlar delar av ämnesinnehållet som de avser att undervisa och hjälpa elevernas meningsskapande av representationerna genom att hålla sig uppdaterade kring elevernas förkunskaper och tolkningar. Det resultat som presenteras i den här avhandlingen visar att det kan vara fördelaktigt att tolka lärande i naturvetenskap i en vidare bemärkelse.
The last five years have truly been a remarkable experience – marked by all sorts of feelings. Being a doctoral student is sometimes stressful, frustrating and challenging, but also creative, fun and exciting. The cover of this dissertation metaphorically illustrates my personal academic development from a little seedling to a blooming orchid. However, orchids also represent several other important aspects of my research and development. They have an upright stem, which represents to me the confidence and courage required to plan and perform research, and make claims based upon the outcome. In addition, orchids are very diverse (comprising one of the most species-rich families on earth), Swedish orchids are currently protected in the whole of Sweden and are very common potted plants in ordinary Swedish homes. These aspects tally with key themes of my research: that learning is a personal experience, but strongly influenced by both one’s social environment and the way that information is presented. Thus, it occurs everywhere: in school, in every home and in every situation through diverse representations.

Furthermore, just as orchids need water, nutrients and support occasionally, doctoral students need encouragement and advice (expressed in appropriate manners and representations) once in a while to keep up our hard work and guide our progress. With too little we wither, with just enough we grow and mature. Lastly, orchids need careful tending, but are perfect gifts, reflecting the time we all need to spend with friends and family in order to learn, thrive and develop our potential. I have been encouraged by numerous people along the way, and I present this thesis as an orchid-like gift, in honour of their contributions to my development, in addition to the traditional aims of any thesis (presenting my research and the conclusions drawn from it).
Numerous people deserve thanks for contributing to my learning and development over the years. It would be impossible to name them all, but those I most want to thank for their help, especially during my time as a doctoral student, include the following.

My supervisor Lena, thank you for believing in me and for letting me be independent, which is much appreciated, and for your tremendous engagement and encouragement – you are brilliant! Huge thanks are also due to all the members of my research group during these years; without your encouragement I would surely have wilted. Lena, Konrad, Mari, Gunnar, Petter, Gustav, Daniel, Nalle, Carl-Johan and Shu-Nu, you all deserve a star! Here I especially want to thank Mari for our joyful and productive talks and for just being you, and Gunnar for your sense of humour and cleverness – you two are such good friends. Thank you to all the people at FontD and TekNaD for being superb colleagues and friends, and for maintaining a positive and constructive atmosphere. Karin, Anna, Lasse, Johanna, Daniel, Jesper, Fredrik, Annika, Cecilia, Claes, Jonas, Thomas, Helge, and Jonte, you have all contributed. In particular, thank you Anna for your friendship, support and patience, Karin for your sensible advise and being my friend, Lasse for your kindness and uplifting nature, and Cecilia for tackling quizzes with me and for our lovely talks. I also need to thank TekNaD and Lena for giving me the opportunity to work from a distance. Moreover, thank you Nina, Carola, and Mats (members of the national FontD group) for making this time cheerful and entertaining. I really hope we can continue the friendly relationships and attend some nice conferences together in the future.

Jan and Trevor, thank you for being excellent co-authors and for both your wisdom and great support for my research! Special thanks to you Trevor, for your welcoming nature during all our trips to South Africa, your engagement and support during the work and great advice about excellent South African wine. Thank you Niklas Gericke and Per Andersson for your helpful comments during my 60%- and 90%-seminars, you both provided me with wise thoughts and guidance. Moreover, thanks are due to John Blackwell of Sees-editing Ltd. for
valuable help with linguistic editing of the thesis and valuable suggestions, an outstanding effort.

Of course, I must also mention my family – my father Jerry, my mother Kristina, my brothers Jimmy and Ronny, my sister-in-law Linda, and nephew Gustav – you all deserve deep and heartfelt thanks for your tremendous love and encouragement, for believing in me. Also, Annica, Anna, Siv, Christer, Linn L., Malin, Linn K. and Emmy, thank for your support and for always caring and asking about my work – which is highly appreciated.

Lovis, my beloved dog, is another major character in my story. She has provided me with endless energy and joy. During my last years of working without daily contact with colleagues her company has been irreplaceable. Lastly, Alf, I thank you for yesterday, today, and tomorrow – you are the love of my life and a special friend.

Yours sincerely,
Caroline

Hermansby, Sweden
February 2013
Prologue
This thesis is based upon research and results presented in the following four appended papers, which are referred to in the text by the corresponding Roman numerals.

Paper I Students’ learning about self-assembly using two different external representations
Gunnar Höst, Caroline Larsson, Arthur Olson, & Lena Tibell
Re-submitted to CBE – Life Sciences Education.
Gunnar, Lena and I jointly planned the study and collected the empirical data. Gunnar and I jointly wrote the paper, while Lena made contributions to analysis of the material, reflections and proofreading. Arthur contributed to production of the tangible model and proofreading.

Paper II Using a teaching-learning sequence (TLS), based on a physical model, to develop students’ understanding of self-assembly
Caroline Larsson, Gunnar Höst, Trevor Anderson, & Lena Tibell
Published (2011) in A. Yarden, & G.S. Carvalho (Eds.), Authenticity in biology education: benefits and challenges. Papers presented at the 8th Conference of European Researchers in Didactics of Biology (ERIDOB), Braga, Portugal.
Gunnar, Trevor, Lena and I jointly planned the study and collected the empirical data. We also made equal contributions to analysis of the material and writing the paper.
List of Papers

Paper III  Challenging students’ intuitive expectations – An analysis of students reasoning around a tangible model of virus assembly
Caroline Larsson & Lena Tibell
Manuscript
Gunnar, Lena, Trevor and I collected the empirical data. Lena and I jointly analysed the material and wrote the paper.

Paper IV  When metaphors come to life – at the interface of visualizations, molecular processes and student learning
Mari Stadig Degerman, Caroline Larsson, & Jan Anward
Mari and Lena collected the empirical material, which was initially presented in Stadig Degerman & Tibell (2011). Mari and I jointly analysed the material and wrote the paper. Jan contributed to the linguistic theoretical framework, reflections and proofreading.

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# Table of Contents

**Abstract**

**Swedish Abstract**

**Prologue**

**List of Papers**

1. Introduction .................................................................................................................. 19  
   A Holistic Approach for Learning .............................................................................. 22  
   Initial Constraints ..................................................................................................... 24  

2. Theoretical Framework .............................................................................................. 27  
   Distributed Cognition ............................................................................................... 28  
   Main Components of Distributed Cognition ............................................................ 28  
   Constructivism ........................................................................................................... 29  
   Social Constructivism ............................................................................................... 30  
   Individual and Social Aspects of Constructivism ...................................................... 31  
   Balancing Elements of the Theoretical Framework .................................................. 32  

3. Representations and Students’ Meaning-making ..................................................... 35  
   External Representations ............................................................................................ 35  
   Metaphorical Language ............................................................................................. 36  
   Metaphors and Analogies ......................................................................................... 37  
   The Relation between Thought and Language ......................................................... 37  
   Representations and Learning .................................................................................... 39  
   Learning with External Representations .................................................................... 39  
   Metaphors and Learning ............................................................................................ 41
# Table of Contents

4. Molecular Processes and Students’ Challenges .............................................. 43
   Common Characteristics of Molecular Phenomena .................................. 43
   The Process of Self-assembly .................................................................. 44
      Tangible Models of Self-assembly .................................................. 46
   The process of ATP Synthesis ................................................................ 47
   Students’ Challenges Associated with Learning Self-assembly and ATP Synthesis ................................................................. 48
      Threshold Concepts ...................................................................... 49

5. Prior Knowledge, Emotions and Conceptual Change ................................... 51
   Prior Knowledge .................................................................................... 51
      Intuitions and Counter-intuitive Concepts .................................... 52
   Emotions ............................................................................................... 53
      Intrinsic Motivation .................................................................... 54
   Conceptual Change ............................................................................... 55
   Intuitions and Conceptual Conflicts ...................................................... 56
   Prior Knowledge, Emotions and Conceptual Change ............................ 57

6. Aims and Research Questions ....................................................................... 61

7. Methodology and Methods .......................................................................... 63
   Qualitative and Quantitative Research .................................................. 63
   Research Design ..................................................................................... 65
      Theoretical Perspectives and Choice of Methods ................................ 66
   Samples and Contexts ........................................................................ 68
   External Representations Used in Studies 1-3 ................................ 70
      The Tangible Model ........................................................................ 70
      The Textbook Image .................................................................... 70
      The Animation ........................................................................... 72
   Instruments ............................................................................................ 73
      Interviews ...................................................................................... 73
      Group Discussion .......................................................................... 73
      Pre- and Post-tests ......................................................................... 74
   Quantitative Analysis ............................................................................. 75
   Qualitative Analysis ............................................................................... 76
# Table of Contents

Data Handling ................................................................. 76  
Data Interpretation ......................................................... 76  
Discussion of Methods ..................................................... 77  
  Reliability ................................................................. 78  
  Validity ................................................................. 79  
  Generalizability .......................................................... 80  
  Limitations .............................................................. 81  
Ethical Considerations .................................................... 83  

8. Summary of Results ....................................................... 85  
  Paper I ................................................................. 85  
  Paper II ................................................................. 86  
  Paper III ................................................................. 87  
  Paper IV ................................................................. 88  
  Additional Results ...................................................... 89  

9. Discussion ................................................................. 91  
  Core Facets of Self-assembly ........................................ 91  
  The Role of Representations for Students’ Conceptual Understanding ................................................. 92  
  Counter-intuitive Aspects of Self-assembly ................................................................. 96  
  Facilitating Students’ Conceptual Change of Self-assembly .................................................. 99  
  The Role of Emotions for Students’ Conceptual Understanding .............................................. 101  
  Conclusions .............................................................. 103  

10. Implications and Future Directions ................................ 105  
  Implications ............................................................ 105  
  Future Research .......................................................... 109  

11. References ............................................................... 111  

12. Appendix ..................................................................... 131  
  Appendix 1: Interview Guide (Studies 1 and 2) ............... 131  
  Appendix 2: Interview Guide (Study 3) .......................... 132  
  Appendix 3: Discussion Guideline (Studies 1 and 2) ........... 134  
  Appendix 4: Discussion Guideline (Study 3) ..................... 136
1. Introduction

We explore, discover and attempt to comprehend our world through experiences provided by our senses. These experiences provide the foundations for our learning and understanding in everyday life and school. However, many objects and processes are far too complex to perceive and comprehend using solely our senses. Thus, in everyday life we often use sketches, diagrams or maps to simplify or highlight important features of objects or processes, compare or contrast them, clarify connections between them and explore changes in them that cannot be directly observed. As Phillips, Norris & Macnab (2010) noted, using an illustration of a horse as an example, the purpose of such representations is to draw attention to certain features of what is represented. The point is not to replace the experience of seeing a horse, but rather to draw attention to certain features of the horse.

We also use various scientific representations to represent abstract relationships or phenomena that are simply too big to comprehend, like the universe. Similarly, we cannot directly experience some objects and processes through our senses because they are far too small to be perceived by human vision, notably molecules and molecular processes in cells. Clearly, knowledge of these phenomena is crucial for fundamental understanding of the world and diverse technological applications. However, they can only be “seen” using instruments such as microscopes or x-ray cameras, which provide various external representations1 or “models” of the phenomena rather than true visual images of them. Strategies used for understanding molecules and molecular processes

1 Throughout the thesis ‘external representations’ refer to any representations that people encounter in their environment, while ‘representations’ includes both external representations and metaphors, see Chapter 4.
1. Introduction

include use of both such external representations and metaphors. However, in molecular life science education, there is another challenge: the purpose of the representations used is not only to draw students’ attention to certain features of a molecular process but also to provide them with an illuminating experience of the process. In this context, representations are essential conceptual tools for building an understanding of this inaccessible molecular world. However, representations display aspects of the world essentially by using similarities (real, supposed or metaphorical) between objects, which may be difficult for students to grasp because of their remoteness from the students’ prior experience.

I developed strong interest in the ways that students perceive and understand the dynamics of molecular phenomena during work towards a teacher education diploma. I interviewed students while they looked at and interacted with an animation portraying the transport of water molecules through a cell membrane. As I talked to the students I realized that they were amazed by the behaviour of the water molecules, or rather the representation of their behaviour in the animation, in which crowds of water molecules were constantly bumping into each other and other molecules. Overall the animation gave a somewhat chaotic impression that the students found interesting and surprising. Several students stated that representations used in teaching at that time, mainly static images, often only showed isolated molecules/particles. This strategy may have been used to reduce the complexity of the cellular environment, in order to more easily highlight certain aspects or processes. Nevertheless, it made me wonder about how students picture the molecular world and the associated movement of molecular entities. This is strongly related to a major pedagogical problem associated with fostering understanding of imperceptible molecular processes: they cannot be clearly related to any directly experienced phenomena, and may be very different from our intuitive expectations. Similarly, Kahneman (2003/2012) describes how we often encounter conflicts in daily life between what our intuitions and logical thinking tell us. For example, if we lose control of a car we are driving in winter we are strongly advised not to use the brake, the most intuitive response. Thus, a key challenge for molecular life science educators is to find successful ways to help students to understand new, sometimes unexpected, phenomena that may
1. Introduction

conflict with their prior knowledge. This challenge, and associated personal and social aspects of learning, became the key themes of my subsequent doctoral research, as described in this thesis.

The subject matter used to explore these issues included two crucial molecular processes in biochemical systems: self-assembly and adenosine triphosphate (ATP) synthesis, or more strictly the phosphorylation of adenosine diphosphate (ADP). Self-assembly refers to the assembly of large molecules (macromolecules) from their components. Nearly all biological complexes (for example ribosomes, membranes, correctly folded proteins and virus capsids) form by processes that involves self-assembly at some stage. However, despite its importance, very little science education research has focused on students’ conceptual understanding of the process. Knowledge of ATP synthesis is also essential for understanding vital life processes, since ATP is used as the primary “energy currency” in all living cells, i.e. to drive numerous energy-requiring reactions. Hence, replenishment of the ATP pool is essential for the maintenance of life.

An initial aim was to review the scientific literature to identify facets of self-assembly that could be relevant for a conceptual understanding of the process and investigate whether it incorporates any counter-intuitive aspects. A further aim was to explore how interactions with representations and peers influence students’ conceptual understandings (and misunderstandings) of the molecular processes of self-assembly and ATP synthesis. The identified facets and counter-intuitive aspects of self-assembly proved to be particularly interesting for the general indications they provide about the impact of various representations on the learning and understanding of phenomena. Clearly, students can have no direct experience of molecular level phenomena, thus a more specific, continuing interest is in identifying ways to use representations that can successfully substitute for this missing experience. The outcome and implications of the research should have clear relevance for both science education researchers and teachers of life sciences at all levels.

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2 Throughout the thesis ‘prior knowledge’ refer to intuitions and prior conceptual understanding, see Chapter 5.
3 Throughout the thesis conceptual elements are referred to as ‘facets’ (cf. Minstrell, 1992).
1. Introduction

A Holistic Approach to Learning

The work this thesis is based upon is a contribution to science education research, more specifically molecular life science education. In the thesis I summarise results and implications from studies described in the four appended papers listed above. However, before doing so I should outline the theoretical framework for learning that has been applied. Traditionally, there has been a strong emphasis on cognitive aspects in education research. However, some authors, notably Zembylas (2005), believe that this emphasis has supported a widely held but erroneous assumption that emotions are solely obstacles for learning. Zembylas and several other authors have challenged this assumption, asserting that it is important to consider aspects of teaching that influence students’ motivation and engagement in science, as a lack of motivation is likely to be one reason for their increasing disinterest in science (Osborne, Simon & Collins, 2003). Furthermore, consideration of affective factors may be particularly important when students encounter new knowledge that conflicts with their prior knowledge (Duit & Treagust, 2012). Thus, we can attain a better understanding of the significant components of students’ learning of scientific subjects by applying a holistic approach (Illeris, 2003; Jarvis & Parker, 2005; Zembylas, 2005). Therefore, in the research this thesis is based upon, my colleagues (the co-authors of the appended papers) and I (hereafter we) applied a framework for understanding learning that incorporates both cognition and knowledge acquisition perspectives, as illustrated in Table 1 and further described in Chapter 2.
### 1. Introduction

Table 1: The theoretical framework for understanding learning applied in the studies underlying this thesis, incorporating elements of cognition-based and knowledge acquisition-based learning theories.

<table>
<thead>
<tr>
<th>Theoretical framework</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Distributed Cognition</td>
<td>Cognition is distributed over systems – It is distributed within and between individuals, between the human body and the material world, and inseparable from culture.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constructivism and Social Constructivism</td>
<td>Knowledge is constructed individually and socially – Culture, language and emotions are important components.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The focal themes of the appended papers, and factors identified as being important for students’ learning about science generally (and molecular life science specifically) are listed in Table 2. These factors are foci of Chapters 3, 4 and 5. As shown in Table 2, external representations and molecular processes are important themes in all four papers, while metaphorical language, the importance of prior knowledge, emotions and the process of conceptual change was addressed in some but not all of the appended papers.

Table 2: Focal themes of the appended papers and important factors for students’ learning about science generally (and molecular life science specifically) addressed in them.

<table>
<thead>
<tr>
<th>Specific factors for learning</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Representations and Students’ Meaning-making</td>
<td>External Representations</td>
<td>Essential for making molecular processes perceivable</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Metaphorical Language</td>
<td>Used for linking abstract science concepts to familiar ones</td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
1. Introduction

Molecular Processes and Students’ Challenges

Chapter 4

Prior Knowledge, Emotions and Conceptual Change

Chapter 5

Molecular Processes

Imperceptible, sub-microscopic dynamic and complex molecular processes

Prior Knowledge

Learners’ prior conceptual understanding and intuitions

Emotions

Intrinsic Motivation

Conceptual Change

The process whereby individuals’ conceptions change over time.

Initial Constraints

The influence of culture on students’ learning was not explicitly investigated in the studies (Papers I-IV), although this element is always present, thus I do not make any general claims related to cultural aspects in this thesis. However, the importance of cultural dimensions is implicitly recognised in the discussion regarding the influence of metaphorical language on students’ learning. Furthermore, as mentioned above, the focus was on meaning-making with respect to just two processes, self-assembly and ATP synthesis. There is a somewhat greater emphasis on self-assembly than on ATP synthesis, since three of the appended Papers (I-III) consider students’ meaning-making about aspects of self-assembly while only one (IV) considers their meaning-making about aspects of ATP synthesis.

Empirical data were gathered in the studies by observations of university students’ meaning-making in two sharply contrasting countries: Sweden and South Africa. However, our intention was not to compare the studied phenomena in the two countries; the research samples and countries were simply
1. Introduction

chosen for their accessibility to the researchers involved. In addition, Paper II
reports some quantitative results that are compared to results presented in a
former version of Paper I that was submitted in 2010 but rejected. Thus, Paper I
has been subject to major changes and some strategies for the analysis have been
changed from those exploited in the former manuscript. I will therefore not put
any emphasis on this specific comparison in Paper II throughout this thesis.
Methodological questions, such as the sizes of the students’ samples,
methodological constraints and the scope for obtaining statistically meaningful
results, will be further addressed in Chapter 7.

Lastly, learning occurs not only in science classrooms but also outside
educational establishments. Thus, the rationale of solely examining learning that
occurs within classroom walls could be questioned. However, since school is
institutionalised and goal-directed we may argue that learning in this sector is of
particular interest for research (Illeris, 2002).
1. Introduction
This chapter describes the theoretical framework of both this thesis and the research it is based upon, which has provided both foundations for methodological choices and discussion of the results. It incorporates elements of both cognitive and human knowledge acquisition perspectives. Merging (to varying degrees) perspectives have been done by several authors, including Dewey (1938), Fägerstam (2012), Illeris (2002), Stolpe, (2011) and Zembylas (2005). Indeed, Illeris (2003) believes that there is a need to revise traditional learning theories and interpret learning much more broadly. He suggests that two types of learning processes should be recognized and considered: an external interaction process and an internal psychological process of acquiring knowledge in relation to prior knowledge. Zembylas (2005) also advocated a more holistic perspective of learning and suggested that three theoretical perspectives (the conceptual change perspective, the socio-constructivist perspective and the poststructuralist perspective) should be applied in attempts to elucidate the learning process.

While reading this chapter, you will see I believe that learning occurs on many planes simultaneously, and that both cognitive and human acquisition of knowledge perspectives can be helpful for illuminating the processes involved. Thus, these perspectives are initially outlined then my theoretical framework, incorporating elements of both, is presented. Briefly, my line of reasoning is that learners construct their understanding of any given subject individually, but their understanding is also influenced by social interaction and the contextual factors, including objects and culture. In addition, learners need to relate new knowledge to their prior knowledge and experiences, thus these factors also significantly influence the learning process.
2. Theoretical Framework

Distributed Cognition

Cognitive science is the interdisciplinary study of cognition and cognitive processes. It emerged in the 1950s as a product of the reorganization of psychology, anthropology and linguistics, in conjunction with the development of neuroscience and computer science as scientific disciplines (Miller, 2003). Initially, researchers in the field were strongly influenced by behaviourism (a psychological approach that emphasizes observable measurable behavior), and cognition was almost entirely attributed to processes in the individual mind. However, subsequently there has been increasing recognition of the importance of social elements of cognition and the social distribution of cognition (Lehtinen, 2003). Researchers who were largely ignored when behaviourism dominated the cognitive science arena, for example Jean Piaget, Jakob von Uexküll, and Lev Vygotsky, began to question the foundations of cognitive science and the dualist-view, which views cognition (the mind) as separate from the body and the surroundings. Consequently, new perspectives such as situated (embodied) cognition and distributed cognition developed (Lindblom & Svensson, 2012). There are some distinct differences between situated and distributed cognition. According to advocates of situated cognition “knowing” is inseparable from “doing”, hence they attach less importance to internal mental processes (Lindblom & Susi, 2012). In contrast, distributed cognition recognises internal mental processes, together with social interaction with artefacts or other human beings and cultural aspects as important components of human cognition (Dahlbäck, Ramsbusch & Susi, 2012).

Main Components of Distributed Cognition

Following from ideas proposed by Vygotsky, Edwin Hutchins (1994) initially developed distributed cognition theory in the 1990s. The theory holds that cognitive resources are shared, which means that individuals’ cognitive processes, objects and the limitations of the environment mutually affect each other (Lehtinen, 2003). Key elements of an educational environment normally include an individual learner, his/her peers, socio-culturally formed conceptual tools and a teacher (Salomon, 1993; Lehtinen, Hakkarainen, Lipponen, Rahikainen &
2. Theoretical Framework

Muukkonen, 1999). Hollan, Hutchins & Hirsh (2000) describe how the theory is tailored for understanding the interaction between people and technology and state three basic assumptions of distributed cognition:

- **Cognition is socially distributed.** This means that cognition and its acquisition is not limited to internal processes, but also includes cognition that is distributed among interacting individuals. Cognition here is interpreted in a broad sense, and includes flows and transformations of information, understandings and misunderstandings resulting from social interactions between people or between people and the environment.

- **Cognition is embodied.** This means that the human body is also considered to be an active part of our cognitive system, since we interact with and relate to our environment through it. However, the relationship between internal and external processes is very complex. Interactions between multiple internal and external resources occur in the mind on diverse timescales, thus the body and its interactions with the material world are key components of our cognitive system.

- **Cognition is inseparable from culture.** Human agents live in complex cultural environments and culture can be viewed as a result of human activity, but culture also strongly influences human activity and cognitive processes. (Hollan et al., 2000)

Hence, activity is shaped and enabled by the resources that are distributed throughout people, environments and situations. This perception has been widely applied as a learning theory in various fields, including computer-supported learning (e.g. Lehtinen, 2003), educational technologies (e.g. Winn, 2002) and distance education (e.g. Dede, 1996).

**Constructivism**

Constructivism is a theory of knowledge, epistemology, which addresses questions like “What is knowledge and how is it acquired?” There are many facets of constructivism, but broadly it holds that people actively construct their own knowledge (Bruner 1990; Piaget, 1960) and hence view the world through
2. Theoretical Framework

individual constructs, like filters, composed of their past subjective experiences. Thus, humans’ mental representations are subjective representations of the world and meanings are inseparable from interpretations. The perspective builds on ideas expressed by Dewey (1938) that learning is a social and interactive process, thus students should develop best in an environment that focuses on fruitful experiences and interaction, organized in a manner that guides students’ learning. According to the broad perspective of constructivism, learners build mental representations of the world, which they use to interpret new information and guide their actions (Driver 1989). Furthermore, learning is viewed as an adaptive process through which learners’ mental representations are reconstructed as their ranges of experiences and ideas expand (von Glasersfeld, 1989). Traditionally, the constructivist view was limited to the individual and how the mind constructs knowledge. However, this was extended in subsequent forms of constructivism, for example social constructivism (Holton, 2010), as discussed in the following section.

Social Constructivism

Social constructivism is a socially orientated form of constructivism that applies constructivists’ theory of knowledge to social settings and focuses on the learning that takes place as a result of interactions (Hung, 2001). Thus, it focuses on relations among actors, actions and situations (Hung, 2001; Roschelle, 1992). The origins of this form of constructivism have recently been attributed to work on cognition and learning by the Russian psychologist Lev Vygotsky (1978), who stressed the importance of culture, social context and emotions for children’s cognitive development. His perception of a link between cognition and emotion is important, because it is usually neglected in other forms of constructivism in science education (Zembylas, 2005). Indeed, the traditional social constructivist view has been interpreted as being too narrow (Nelmes, 2003; Op’t Eynde, De Corte & Verschaffel, 2006; Zembylas, 2005) due to its failure to acknowledge sufficiently the link between cognition and emotion.

From a social constructivist’s perspective, people construct knowledge in collaboration with others, hence knowledge creation is shared (Prawat & Floden, 1994). Knowledge is constructed socially, but is then assimilated by individuals.
Thus, in complex interactions with cultural factors (and emotional responses), learners’ different interpretations of, and hypotheses about, the environment influence the process of knowledge construction. As we act with each other and the environment we create meaning (Prawat & Floden, 1994), thus knowledge that learners discover and construct are shaped by their culture and background (Wertsch, 1998). Kukla (2000) even argues that we construct what is real through our actions. Moreover, social constructivism holds that teachers should be actively involved in the learning process, providing guidance and structure for the students’ acquisition of knowledge (Hmelo-Silver & Barrows, 2006). Learners build connections between their prior knowledge, what they already know, and the world around them.

Individual and Social Aspects of Constructivism

Both individual and social factors significantly influence the learning process. Hung (2001) compares some of the key concepts of four of the dominant learning theories, and Table 3 compares advocated learning modes, type of learning required, instructional strategies and key concepts of constructivism and social constructivism.

<table>
<thead>
<tr>
<th>Advocated learning modes</th>
<th>Constructivism</th>
<th>Social Constructivism</th>
</tr>
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<tbody>
<tr>
<td>Personal discovery and experimentation</td>
<td>Mediation of different perspectives through language</td>
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<tr>
<th>Advocated types of learning</th>
<th>Constructivism</th>
<th>Social Constructivism</th>
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<tbody>
<tr>
<td>Problem-solving in realistic and investigative situations</td>
<td>Collaborative learning and problem-solving</td>
<td></td>
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<tr>
<th>Advocated instructional strategies</th>
<th>Constructivism</th>
<th>Social Constructivism</th>
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</thead>
<tbody>
<tr>
<td>Provide for active and self-regulated learner</td>
<td>Provide scaffolds to assist the learning process</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Key concepts</th>
<th>Constructivism</th>
<th>Social Constructivism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal discovery generally from first principles</td>
<td>Discovering different perspectives and shared meanings</td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Hung (2001, p. 284)
Hung (2001) also advocated merging the two schools of constructivism and social constructivism, to recognise the importance of both individual and social dimensions of learning. In this combined perspective: learning is considered to be an active process of constructing knowledge; knowledge can also be constructed socially with inputs from individuals; and the interpretation process is interactively influenced by individuals’ prior knowledge and beliefs, together with elements of their social and cultural context (Hung, 2001).

Balancing Elements of the Theoretical Framework

In my view learners construct their understanding of any given subject individually but the process is strongly influenced by social interactions and the context, which also includes objects and culture. The perspectives of distributed cognition, constructivism and social constructivism are complementary. By viewing cognition as distributed, rather than being restricted to individuals’ mental processes, we recognise representations and cultural elements (such as external representations and language) as important components of the cognitive system. Thus, we can infer that some parts of individuals’ thought processes interact with elements of the social and material context. Recently attempts have been made to extend distributed cognition theory to incorporate embodied aspects of cognition, which holds promise to embrace aspects of cognitive processes within individuals (Dahlbäck et al, 2012). However, currently it mainly focuses on system-level processes, therefore I also include the learning theory of constructivism, which focuses on individuals’ knowledge construction, in my theoretical framework. Here, social constructivism considers individuals’ knowledge construction as well as knowledge construction in a socially shared context; learning is neither entirely private, nor is it shaped solely by external factors (McMahon, 1997). Dewey’s (1938) emphasis on the importance of fruitful experiences and interaction for successful learning is also highly relevant to the discussion throughout this thesis.

I advocate that it is important to examine certain aspects of learning separately, but also to employ a holistic approach (Illeris, 2003). In accordance with Zembylas (2005), I believe that we need to consider the interplay between emotions and cognition to obtain a deeper understanding of learning in science.
2. Theoretical Framework

Merged perspectives of distributed cognition, constructivism and social constructivism also guided the designs of the studies described in the four appended papers (see Table 4, p. 67). In addition to the more general views of cognition and knowledge acquisition presented above, the following Chapters consider specific factors that are important for learning science generally and molecular life science particularly. These are learning through representations, molecular processes, prior knowledge, emotions and conceptual change.
2. Theoretical Framework
3. Representations and Students’ Meaning-making

A challenge facing molecular life science professionals, students and teachers is that molecular scale events and processes are invisible (Tibell & Rundgren, 2010). Hence, representations (linguistic, graphical and mathematical models) are essential conceptual tools for the scientific activities not only of teachers and learners, but also those of experts as they elaborate hypotheses and seek explanations for molecular phenomena (Kozma, Chin, Russell & Marx, 2000; Coll, France & Taylor, 2005). Some researchers argue that humans need external support and assistance due to our rather limited cognitive resources, such as memory and reasoning abilities (Norman, 1993). Representations also provide students with information that other means of instruction do not (Phillips et al., 2010). Throughout this chapter, and the entire thesis, I refer to representations in physical forms as external representations (e.g. images, models or animations), representations in verbal linguistic forms as metaphorical language and representations in an individual’s mind as internal representations. These concepts are described and discussed in more detail in the following sections.

External Representations

Zhang & Norman (1994) have described a theoretical framework for studying the processes that occur when humans are tackling distributed cognitive tasks (i.e. tasks that “require the processing of information distributed across the internal mind and the external environment…which together represent the abstract structure of the task”). As outlined above, I follow the cited authors’ definitions of internal representations (propositions, productions, schemas, mental images or other representations in individuals’ minds) and external
representations (physical symbols, external rules, constraints, or relations embedded in physical configurations encountered in the environment).

All external representations represent aspects of the world (or abstract conceptual constructs) by using similarities between them and that which they are representing (Giere, 2004). However, there are numerous kinds of external representations, and they can be classified in various ways. Common kinds include: static diagrams or images conveying information in two dimensions according to how their components are spatially arranged (Schnotz, Picard & Hron, 1993); tangible models conveying information in three spatial dimensions; and animations, which are often used for showing changes in phenomena over time. Some also enable people to experience representations of phenomena (e.g. a biochemical process) in more than one sensory modality (e.g. Birchfield et al., 2008), for instance both visually and haptically, i.e. through touch (Bivall, 2010; Minogue & Jones, 2006). There are also various kinds of models. For example, Black (1962) defined five types of models, one of which (the “analogue model”) manifests “a point-by-point correspondence between the relations it embodies and those embodied in the original”.

**Metaphorical Language**

The language used in science is highly domain specific and the role of language in research and learning in science has been investigated by various authors (e.g. Duit, 1991; Lemke, 1990; Reif & Larkin, 1991; Tibell & Rundgren, 2010; Treagust, Harrison, & Venville, 1996/1998). Many of the scientific terms used in physics are also used in everyday language, which may be a source of confusion for students. In contrast, terms used in molecular life science do not usually have any equivalents in everyday language, which may be an advantage (Tibell & Rundgren, 2010). However, this lack of everyday meaning makes it difficult to reason about abstract molecular processes (Reif & Larkin, 1991). Therefore, the language used in molecular life science includes numerous metaphors, analogies, acronyms, anthropomorphic and teleological expressions (Tibell & Rundgren, 2010), which are important conceptual tools for researchers and students (e.g. Duit, 1991; Treagust, Harrison, & Venville, 1996/1998).
3. Representations and Students’ Meaning-making

Metaphors and Analogies

Both teachers and learners use metaphorical language as a way to relate molecular phenomena to more familiar ones from everyday life. Moreover, textbooks are rich in metaphors, analogies, and intentional expressions, which teachers also repeatedly use them to help students gain a deeper understanding of scientific concepts (e.g. Orgill & Bodner, 2006).

Aubusson, Harrison & Ritchie (2006) review the diverse definitions of, and differences in, analogies and metaphors used in the scientific literature, and conclude that the term metaphor can be used for all comparisons through similarity between two objects or processes. In contrast, analogy seems to be used for descriptions of similarities or differences between objects or processes. They conclude that “all analogies are metaphors but not all metaphors are extended into analogies” and “the comparisons in a metaphor are covert whereas in analogy these are overt”. Their reasoning is compatible with a view expressed by Lakoff & Johnson (1980), that metaphors implicitly inform the way we think and act, and the structure-mapping theory of Gentner (1983). However, the second we start to scrutinize any given metaphor it remains a metaphor but at the same time becomes an analogy (Aubusson et al., 2006). In Paper IV we use the term metaphor for the studied words related to the process of ATP synthesis because the difference in meaning between their use in the familiar and the scientific contexts is so pronounced, involving a mapping of concepts from an artificial macroscopic domain level to a sub-microscopic, biochemical process domain level. Moreover, the identified metaphors may remain covert for students, while we as researchers scrutinize the metaphors and analogously extend their meaning in relation to the process.

The Relation between Thought and Language

Essentially, there are two main explanatory perspectives of the relationship between thought and language: that language mainly determines thinking or that thinking mainly determines language. However, the relationship between language and thought (as well as its relationship to individuals’ conceptions of the world), is still under debate and probably some thinking is bound to language
3. Representations and Students’ Meaning-making

and some is not (Allwood, 2000). Vygotsky (1978) held that speech connects children’s constructed meaning of the world, attained through their actions, with the common perception of the world in their particular culture. Thus, language is both a highly personal and social process (Vygotsky, 1978); an idea amplified by Hung (2001), who claimed that social factors, including language, influence and shape individuals’ perceived reality. Both perspectives are compelling and useful for examining the relation between thought and language in connection to learning science. However, Allwood (1983) proposed a synthesis, postulating that thoughts are primary but can be influenced by conservative collective language, based on the following two assumptions:

1. We can think without language but we cannot speak without thinking.
2. It is likely that language-dependence exists, at least as an important factor for learning to point at and draw attention to concepts and ideas.

Allwood (1983)

According to Allwood’s synthesis, thinking can always exist without audible speech. Furthermore, the relationship between thinking and language is stronger in social organisations and language plays an important role for individuals’ learning and socialisation. In this context, language is a collective stabiliser for conceptualisation, which facilitates learning of concepts that are important for a particular organisation that are not based on perception or motor skills (Allwood, 1983). This is further supported by Hung (2001), who suggests that humans in a given discourse develop similar expectations of reality based on the similar use of language to approach the world: to reach understanding, co-ordinate action and socialize. Learners can use language as a facilitator for learning new conceptions and use partly verbalised elements in their thinking. However, novices may initially be quite dependent on the explicit meaning of language and linguistic expressions, but as their knowledge develops this dependence decreases, and the importance of language in learning implies that language is a vehicle of our collective, social and cultural inheritance (Allwood, 1983).
3. Representations and Students’ Meaning-making

Representations and Learning

It is widely accepted that representations can support learning and thinking. Indeed, when learning about imperceptible objects or processes, representations can not only support, but are essential resources for, students’ meaning-making. However, they must be used appropriately with respect to students’ prior knowledge, cognitive abilities and learning skills (Phillips et al., 2010). Thus, establishing appropriate relationships between representations used and students’ prior knowledge is essential for learning about imperceptible phenomena (Justi & Gilbert, 2002). However, difficulties in interpreting representations are potential obstacles to learning and understanding in science. For example, Schönborn, Anderson & Grayson (2002) describe how such difficulties can result in alternative conceptions and incorrect ways of reasoning.

Learning with External Representations

External representations are important tools for learning since they can help students to see complex relationships in the form of visual-spatial (or other) relations (Uttal & O’Doherty, 2008). Indeed, these authors claim that “It is almost impossible to imagine working in complex visual-based sciences such as chemistry or geoscience without the insights that ‘visualizations’ can afford”. Accordingly, Schönborn et al. (2002) state that diagrams and models are very important tools in teaching biochemistry, as they help students to form kinds of mental models, which help them to understand and perceive different phenomena. Similarly, the use of models in chemistry education is almost a shared practice that can assist students to develop internal representations of chemical phenomena (Chittleborough & Treagust, 2007). However, as Uttal & O’Doherty (2008), Giere (2004) and others have noted, creators of external representations represent the focal phenomena, rather than the representations per se. Thus, for students to benefit from representations they must first realize that they correspond to something else, that they are models of certain concepts or objects, and the relationship between an external representation and the concepts it represents may remain elusive for a novice learner. This is a critical point, because during the last decade the range and availability of technological
Representations and Students’ Meaning-making

displays, and their use in teaching and learning, has increased immensely. However, to be truly useful educational tools, it is essential to ensure that students grasp the connections between what they represent and the represented phenomena.

Despite the vivid use of illustrations in textbooks, teachers’ efforts to teach students about molecular properties and processes are not always successful. A common reason for the lack of success, according to McClean et al. (2005), is that the illustrations are two-dimensional tools intended to illustrate phenomena that occur in four dimensions (three spatial dimensions and time). Many important phenomena also occur in highly complex fractal environments. A possible way to address this problem at least partially, proposed more than a century ago (e.g. Montessori, 1912), is to use tangible models. The use of tangible models in chemistry education became common in the beginning of the 20th century (Petersen, 1970), as molecular models of ball-and-stick types were increasingly used in teaching and research. Later, in the 1950s, several good space-filling models also became available for various types of educational studies (Petersen, 1970), for example investigating learning gains from their use (e.g. Copolo & Hounshell, 2005).

Gabel and Sherwood (1980) propose that manipulation of a tangible model can enhance students’ long-term understanding, and there is abundant evidence that use of such models has positive effects on students’ learning of biomolecular topics (e.g. Harris et al., 2009; Roberts, Hagedorn, Dillenburg, Patrick, & Herman, 2005; Rotbain, Marbach-Ad, & Stavy, 2006). Notably, Dori and Barak (2001) found that using a combination of virtual and tangible models can enhance students’ understanding of molecular structures in learning chemistry and develop their spatial ability. Both Harris et al. (2009) and Roberts et al. (2005) found that students perceived tangible models to be the most helpful tools for learning about protein structure and function. Harris et al. (2009) also concluded that students preferentially used tactile models when challenged with questions that required higher-level thinking about genetic phenomena. Similarly, Rotbain et al. (2006) found that giving genetics students either illustrations or a physical model improved test results, but the answers from the group given the physical model were more correct and profound.
Pillay (1998) compared students’ learning of spatial representations in four structural formats, and found that physical (tangible) models were most helpful for students in an assembly task, since students only needed to interpret the information provided and did not have any problems with hidden structures. Hageman (2010) found that students who constructed models of biochemical structures on a weekly basis during part of an introductory biochemistry course gave more sophisticated answers than controls in subsequent exams, and that more complex structures were constructed in small-group activities. Moreover, the use of discussions of an exploratory nature with hands-on practical activities reportedly has positive effects on learners’ cognitive development (Webb & Treagust, 2006) and active hands-on manipulations seem to promote the learning of complex and abstract science concepts (e.g. Glasson, 1989; Vesilind & Jones, 1996). In addition, tangible user interfaces (Ishii & Ullmer, 1997) have received considerable attention recently (e.g. O’Malley & Stanton Fraser, 2004). There is still a need for more empirical studies of their potential (Marshall, 2007; Marshall, Rogers, & Hornecker, 2007), but some of the expressed benefits of such models are that they promote exploration (Rogers, Scaife, Gabrielli, Smith, & Harris, 2002), collaboration (Marshall, 2007), and engagement (Price, Rogers, Scaife, Stanton & Neale, 2003).

Metaphors and Learning

Aubusson, Harrison & Ritchie (2006) highlight a paradox related to teaching and learning with metaphors and analogies, “…that analogy both misleads and leads people to better understanding…”. Metaphors derive from experiences; in an educational context this implies that prior knowledge of the real-life domain, as well as the scientific domain, provides foundations for students’ use of metaphorical language. However, the matches between concepts in the two domains are never perfect. Thus, for successful meaning-making students need to know which characteristics of a metaphor are relevant thereby enabling intuitive interpretation of the metaphorically described phenomenon. With limited prior knowledge and little experience, the metaphors might be taken literally (Gallese & Lakoff, 2005) and can cause students difficulties. This is particularly true if
metaphors (or analogies) are not explained or elucidated, as Orgill & Bodner (2006) found for many analogies in biochemistry textbooks they examined.
Since molecular level biological processes and events are highly complex, invisible and intangible, they are described in molecular life science using complex, abstract concepts that are deeply rooted in diverse 'pure science' and 'applied science' disciplines (Tibell & Rundgren, 2010). Thus, molecular processes may pose various inherent challenges for learning. This chapter provides a brief introduction to the nature of molecular processes, in particular molecular self-assembly and ATP-synthase catalysed synthesis of ATP, highlighting some of the challenges associated with learning these processes.

Common Characteristics of Molecular Phenomena

The subject matter in molecular life science has some common characteristics that are unique for this particular domain, and although the molecular world can be fascinating, these characteristics may create obstacles to learning for novices (Johnstone, 2000). Many identified learning difficulties are linked to the general complexity of molecular processes, the numerous factors that generally influence them and the multi-level abstract frameworks used to describe them, which make it difficult to see the overall picture (Tibell & Rundgren, 2010).

The sizes of atoms, molecules, and cells appear to be difficult for students to conceptualize, and thus attain understanding of the molecular world (Westbrook & Marek, 1991), in two major respects. They often hold a range of misconceptions related to the size of molecules and atoms per se (Griffith & Preston, 1992), and the dimensional relationships between imperceptible sub-microscopic level objects and perceivable macro level objects are challenging for them to grasp (Bahar, Johnstone & Hansell, 1999). In addition, Flores, Tovar &
Gallegos (2003) have proposed that students’ problems with understanding cells are due to difficulties in grasping relationships between the structure and function of cellular components and to discriminate between organ and organism level phenomena.

As molecular processes and entities are not within the range of human vision they cannot be experienced directly. Neither can they be controlled in the perceivable world. Lakoff and Johnson (1980) claim that there are two types of concept: direct and imaginative. Direct concepts are grounded in our experience of the physical and social environment, including perception and body movement. In contrast, imaginative concepts are not grounded in direct experience and have no relationship to everyday life. Such concepts are formed from external inputs and imagination. Concepts regarding sub-microscopic scale are inevitably imaginative, since they are imperceptible and have no equivalents in humans’ everyday life.

**The Process of Self-assembly**

Self-assembly refers to the random and reversible formation of complexes from lower-order components via (generally) weak interactions. The process of self-assembly is the focus of Papers I-III. It is a core concept in biochemistry and relevant to diverse processes. In fact, most biological complexes and many biological structures (for example ribosomes, membranes, correctly folded proteins, virus capsids and vesicle buds) form by a process that involves self-assembly at some stage (Hinshaw & Schmid, 1995; Kushner, 1969; Lindsey, 1991; Olson, Hu, & Keinan, 2007; Shnyrova et al., 2007; Whitesides & Grzybowski, 2002).

The terminology used to describe self-assembly, and related phenomena, varies among different authors and scientific fields. Consequently, several authors have discussed the definition of self-assembly and how it relates to other pattern-forming processes. The terms self-assembly and self-organisation are often used interchangeably to describe the phenomenon of order arising spontaneously in a system with no external control, but some authors have attempted to differentiate the two concepts. Notably, Halley & Winkler (2008) propose that self-assembly should be used to denote pattern formation in systems that tend towards
equilibrium, and self-organization to denote pattern formation in nonequilibrium systems that require an energy source. They use the following definition of self-assembly:

*Self-assembly is a nondissipative structural order on a macroscopic level, because of collective interactions between multiple (usually microscopic) components that do not change their character upon integration into the self-assembled structure. This process is spontaneous because the energy of unassembled components is higher than the self-assembled structure, which is in static equilibrium, persisting without the need for energy input.*


Whitesides, Mathias & Seto (1991) list several key features of self-assembling molecular life systems. Most importantly, the resulting structure must be in a thermodynamically stable, but reversible and near-equilibrium state that allows error-correction. The stability of the final structures formed in biological self-assembling systems is ensured by cooperatively reinforcing interactions, including van der Waals forces across extensive areas of complementary surfaces in contact and/or numerous hydrogen bonds.

A criticism of using the term self-assembly is that it could be easily interpreted as indicating that the process occurs, and the level of order is increased in the focal system, independently of its surroundings. This conflicts with the second law of thermodynamics, since the decreased degrees of freedom following assembly would result in decreased entropy if the system only contained the self-assembled components. It is therefore important to also take the surroundings of the self-assembling system into account. Uskokovic (2008) holds that the term is misleading because it ignores the events and increase in entropy in the immediate environment that occur in parallel with the assembly process. Instead, Uskokovic suggests that the term self-assembly should be replaced with "co-assembly". Halley and Winkler (2008) also recognize the importance of extrinsic factors related to the process of self-organization. Whitesides and Grzybowski (2002) use self-assembly to describe all autonomous pattern formation from components, but distinguish between several different
4. Molecular Processes and Students’ Challenges

Types of self-assembly: static, dynamic, template and biological. Their use of the term static self-assembly seems similar to self-assembly as defined by Halley and Winkler, whereas dynamic self-assembly appears to correspond to self-organization. In the papers appended to this thesis, we use the term self-assembly in the sense suggested by Halley and Winkler (2008).

Tangible Models of Self-assembly

Many processes that involve self-assembly are illustrated in molecular life science textbooks by static images. Similarly, self-assembly is often presented in animations of molecular processes (e.g. www.molecularmovies.com). In most cases the aim of such animations is not to visualize the principles of self-assembly per se, but rather the associated biological process and/or the context (e.g. McClean et al., 2005). My co-authors and I are not aware of any previous evaluations in the science education literature of the educational benefits of a tangible model designed to help students learn about self-assembly in a biologically relevant system. Several authors have presented models of self-assembly, including: models consisting of LEGO bricks with attached magnets used to construct systems that self-assemble in various ways (Campbell, Freidinger & Querns, 2001; Jones, Falvo, Broadwell & Dotger, 2006); others that employ capillary forces between objects such as soda straws (Campbell, Freidinger, Hastings & Querns, 2002) or breakfast cereals on the surface of a liquid that self-assemble into extended structures (Dungey, 2000). The cereal models are similar to bubble raft set-ups that have been used to illustrate the properties of the close atomic packing in metals (Geselbracht, Ellis, Penn, Linsensky, & Stone, 1994). However, none of the models used in the cited studies represent a biologically relevant system or self-assembly in three dimensions. The previous studies have not evaluated the potential educational benefits of the models either. In contrast, in Papers I-III we explore the educational benefits of a tangible model of self-assembly designed to mimic the self-assembly of poliovirus capsids designed by Olson et al. (2007). The model is interactive and readily shows the dynamics of the process and how components attach to each other over time. Thus, it should be appropriate for conveying dynamic and emergent concepts.
The Process of ATP synthesis

The process of adenosine triphosphate (ATP) synthesis, or more strictly phosphorylation of ADP, in the inner membrane of the mitochondrion, is the biochemical focus of Paper IV. As outlined in Chapter 1, ATP is essential for cellular metabolism (and hence numerous vital life processes, such as construction of macromolecules) because it is the primary energy currency in all living cells (Alberts et al., 2008). It is highly suitable for this role, because cleavage of its terminal phosphoanhydride bond, yielding adenosine diphosphate (ADP) and phosphate, releases a suitable amount of free energy for driving diverse biological reactions that are coupled to its dephosphorylation (Stroud, 1996). Thus, continuous replenishment of the ATP pool is essential.

In the simplest terms, in aerobic (oxygen-dependent) metabolism in humans and animals, glucose and other molecules (substrates) obtained from food are degraded to carbon dioxide and water through oxidation (removal of electrons). Some of the chemical energy released during their degradation is used to synthesise ATP, via ADP phosphorylation, and another key metabolic agent, NADH (reduced nicotinamide adenine dinucleotide). This energy currency then drives cellular metabolism. There are, of course, numerous variants. For example, many of the substrates are generated by photosynthesis in most plants and by chemolithotrophic processes in some microbes. In addition, if insufficient oxygen is available, some of the substrates may be only partially oxidised, and in anaerobic organisms, which cannot tolerate oxygen, all of the substrates are partially oxidised (“fermented”) (Alberts et al., 2008).

In slightly more detail, in aerobic metabolism most ATP production in cells occurs at the inner membrane of the mitochondrion. The electrons that are produced during oxidation of substrates are transferred from NADH (and FADH₂) to oxygen via a series of membrane proteins and other organic molecules, the electron transport chain, embedded in this membrane. This chain of reactions drives the transport of protons from the inside to the outside of the mitochondrial inner membrane, creating a gradient of protons over the membrane. This proton gradient, in turn, drives ATP synthesis via oxidative phosphorylation (addition of a phosphate group to ADP). The last protein in the electron transport chain is called ATP synthase, which catalyses the oxidative
phosphorylation (Weber & Senior, 2003). Thus, loosely, ATP synthase is a membrane-bound protein that synthesizes ATP. Note also that the process of ATP synthesis is in principle reversible, the direction of the reaction is dependent on the relative concentrations of hydrogen ions on the opposite sides of the membrane, hence it is *chemiosmotically coupled* to the gradient of hydrogen ions (Yoshida, Muneyuki and Hisabori, 2001).

**Students’ Challenges Associated with Learning Self-assembly and ATP Synthesis**

Learning difficulties associated with understanding molecular processes have been widely discussed in the science education literature. In this section I consider some of these discussions that are particularly relevant to students’ conceptual understanding of self-assembly and ATP synthesis.

According to an on-going molecular life science concept inventory project (Howitt, Anderson, Costa, Hamilton & Wright, 2008; Sears, 2008) self-assembly is one of nine “big ideas” that are important for molecular life science students to learn. Understanding the nature of self-assembly is essential for grasping how complex structures in living cells are formed. Moreover, five of the nine “big ideas” (Howitt et al., 2008; Sears, 2008) are connected in some way to cell metabolism and ATP synthesis. These are regulation, catalysis, energy and organization, and the complexity of molecular structures (Stadig Degerman, 2012). Furthermore, current conceptual understanding of both self-assembly and ATP synthesis incorporates several core concepts in molecular science that have been shown to be difficult for students to learn. In addition, both processes have emergent and complex properties, resulting from interactions between multiple components (Jacobson, 2001). Thus, it might be difficult for students to achieve an integrated understanding of the numerous aspects required to grasp the concepts.

More specifically, students have been found to have difficulties in understanding that momentum is conserved (McCloskey, 1983) and diffusion (Friedler, Amir, & Tamir, 1987; Garvin-Doxas & Klymkowsky, 2008; Odom & Barrow, 1995; Westbrook & Marek, 1991). For example, students often
interpret diffusion as a directional process rather than one dependent on random interactions. Garvin-Doxas & Klymkowsky (2008) also found that students may understand the randomness of diffusion but be unable to connect it to emergent behaviour in systems and well-defined/directed biological processes (Kottonau, 2011). Other studies suggest that students have difficulties in conceptualising the particulate nature of matter (Gabel & Samuel, 1987; Harrison & Treagust, 2002), especially the intrinsic motion of particles and their interaction with other particles (Novick & Nussbaum, 1978). This is a major educational concern since understanding the particulate nature of matter is crucial for understanding numerous science concepts, for example properties of matter, phase changes, chemical reactions and equilibrium (Nakhleh, 1992; Nakhleh, Samarapungavan & Saglam, 2005; Novick & Naussbaum, 1978; Stavy, 1991). Students have similar difficulties with understanding the reversibility of reactions (e.g. Banerjee, 1991; Villafañe, Loertscher, Minderhout, & Lewis, 2011). Although students encounter the concept of chemical equilibrium in several high school, college and higher education courses they still seem to have difficulties with the subject in advanced chemistry courses (Thomas & Schwenz, 1998). Similarly, Banerjee (1991) has shown that both undergraduate chemistry students and in-service teachers have diverse alternative conceptions of various aspects of chemical equilibrium.

No explicit explanations for these difficulties have been provided, but it has been proposed that their sources lie in the everyday experiences that students bring into the learning situation (Nussbaum & Novick, 1982), meaning (for instance) that the particulate nature of matter contradicts their sensory perception of matter. However, several researchers have suggested that students’ expectations derived from experiences in everyday life could be a source of students’ difficulties in understanding key science concepts, such as those mentioned above (e.g. Cousin, 2006; Nussbaum & Novick, 1982). The role of students’ intuitive ideas for their learning will be further addressed in Chapter 5.

Threshold Concepts

In response to identified student learning difficulties, Meyer & Land (2003) propose the existence of threshold concepts, which are understood to be crucial for
students’ understanding and progress in a given domain since they are more general concepts that can be applied across several content areas and are integrated in other processes and concepts. Proposed threshold concepts include randomness, thinking at submicroscopic & subcellular levels, thermodynamics, scale (temporal and spatial), probability and dynamics (Ross et al., 2010). When internalizing threshold concepts we move from one state of knowing to another (Kabo & Baillie, 2009), and transform our way of thinking about a discipline (Meyer & Land, 2003).

The term “threshold” implies that there is something special and perhaps particularly difficult about these concepts. The literature suggests that threshold concepts could be difficult to grasp and are, or may lead to, what Perkins (1999) refers to as “conceptually difficult knowledge”. Moreover, some researchers have suggested that mastery of a threshold concept can be hindered by common sense and intuitive understandings (Cousin, 2006) and Perkins (1999) suggests that conceptually difficult knowledge may also be counter-intuitive. Meyer and Land (2006) describe how learners enter a liminal, unstable, state when trying to grasp these concepts and shift from one state of knowing to another. These transitions are regarded as transformable, irreversible, integrative and troublesome (Meyer & Land, 2003). The threshold concepts listed by Ross et al. (2010) are all in some way vital components for grasping the process of self-assembly and ATP synthesis.
5. Prior Knowledge, Emotions and Conceptual Change

Prior Knowledge

It is widely acknowledged now that humans strongly depend on prior knowledge when trying to make sense of the world and the information they receive through their senses. Ausubel’s (1968) statement of this recognition may be the most well-known: “the most important single factor influencing learning is what the learner already knows”. In general, the amount and quality of prior knowledge influence both knowledge acquisition and the capacity to apply higher-order cognitive problem-solving skills (Ausubel, 1968). More fully, our internal mental representations arise from experiences of events, objects or situations, and the way they normally occur, which we use to interpret, predict and make assumptions about new situations and knowledge (Glaser, 1983). Accordingly, students’ background knowledge significantly influences their learning of sub-microscopic chemical processes (Chittleborough & Treagust, 2007).

Research have shown that both domain-specific prior knowledge and domain-transcending prior knowledge are held to be essential for human learning and part of our knowledge base (Dochy, 1992; Dochy, Moerkerke & Martens, 1996; Glaser, 1983). Indeed, Dochy et al. (1996) and Dochy, de Ridt & Dyck (2002) define prior knowledge as comprising “the whole of a person’s knowledge”. Hence, prior knowledge is dynamic and available for students before a learning task. It is both explicit and tacit in nature and has both conceptual and metacognitive components. Domain-specific prior knowledge have especially been shown to influence students’ achievement (Dochy, 1994). This knowledge is unlikely to be transferred from one domain to another if no explicit transfer-
inducing instruction is given (Dochy, 1992). ‘Prior conceptual understanding’
and ‘intuitions’ are of particular interest in this thesis. Conceptual understanding
refers to understanding the relations between units of knowledge in a domain
and of the principles that govern a domain (Rittle-Johnson, Siegler & Wagner
Alibali, 2001), while intuitions are beliefs that come quickly and spontaneously
to mind (Kahneman, 2003), based on one’s generalisations of experiences of
diverse circumstances in life. Both intuitive (naïve) and scientific conceptual
understanding is regarded as unarticulated generalisations from experiences that
are loosely connected to other elements of knowledge, which may, or may not, be
activated depending on context (Hammer & Elby, 2002; Smith III, diSessa &
Roschelle, 1994; Tirosh, Stavy & Cohen, 1998). Based on a constructivist view
of knowledge and learning both types of prior knowledge have a major impact on
students’ learning (Driver, Guesne & Tiberghien, 1985; Smith III et al., 1994).

Intuitions and Counter-intuitive Concepts

Although researchers have not reached agreement about how concepts should
ideally be presented, we know that human common-sense notions about the
domain in question are relevant (Upal, Gonce, Tweney, and Slone, 2007;
Reasoning refers to deliberate thinking, for example mathematical calculations,
which require effort, while intuitive thoughts come spontaneously to peoples’
minds without any conscious act or effort. This division is attributed by
Kahneman & Frederick (2002) to two types of systems in the human mind. The
first (intuitive) is automatic, fast, requires very little or no effort, and we have
no voluntary control of this system. The second system (reasoning) requires
attention to perform effortful mental activities, is slow, and logical. Impressions
and feeling originating from intuitions are postulated sources of individuals’
explicit beliefs and foundations of reasoning. However, some of our rational
mental activities become automatic (intuitive) if we practice them for a
sufficiently long period of time (Kahneman, 2003; Kahneman & Frederick,
2002).

This dual-system model has numerous implications, particularly in relation
to intuitive and counter-intuitive notions. Kahneman (2003) and Kahneman &
Frederick (2002) suggest that intuitions provide our reasoning with suggestions, in the form of impressions, feelings and impulses. If our rational system endorses these suggestions and impulses they are turned into beliefs and voluntary actions. When all goes smoothly we accept the suggestions of our intuition system. However, if our intuitions cannot provide an answer to a question, for example when something violates an intuitive model of a familiar situation, reasoning is activated to help address the question. In a later publication, Kahneman (2012) describes how we often encounter conflicts between the two systems in daily life, as in the example mentioned in Chapter 1 regarding the counter-intuitive recommendation not to use the brakes if a car we are driving skids on ice. Illusions provide several similar examples. After studying concepts and ontologies of religious representations, Boyer (1994) proposed that humans have a set of intuitive ontological expectations about the properties of any given category, and concepts that do not meet these expectations are experienced as counter-intuitive. Kahneman holds that one of the key tasks of our reasoning system is to check, control and overcome (when necessary) impulses/suggestions originating from our intuitions. However, it is often difficult to avoid errors resulting from erroneous intuitive thought since our reasoning needs valid cues to address (or explanations for) conflicts between intuitive expectations and encountered problems or situations.

**Emotions**

Most of the prominent classical philosophers developed theories of the meaning of emotions, and Vygotsky (1978) claimed that without emotions no learning occurs (see also Mahn & John-Steiner, 2008). Nevertheless, researchers during the 20th century generally neglected this dimension. However, emotions have once again become noteworthy in philosophy, cognitive science, and science education. In science education the significance of emotions in learning has been stressed by, *inter alia*, Alsop & Watts (2002) and Reiss (2005). Modern learning theories also highlight the importance of considering emotions. For example, Knud Illeris (2002/2003/2007) considers an emotional dimension of feelings and motivation to be one of three significant dimensions for learning. In addition, the Rose International Comparative Research Project has found that emotional
factors strongly influence students’ learning and motivation to learn science (Jidesjö, 2012).

Diverse theories about the underlying mechanisms of emotions have been developed, including some that are generally applied within single disciplines and others that are cross-disciplinary. However, emotions and emotional are used as general terms for referring to feelings that appear to be related to learning science (Zembylas, 2005). In the following sections I consider emotions that appear to be related to intrinsic motivation, namely interest and enjoyment.

**Intrinsic Motivation**

Theoretical perspectives of intrinsic motivation are far from new. For instance, in *The Republic* Plato (ca. 380 BC) proposed that the human soul is divided into three parts, each of which has desires. More recent theories hold that humans have motivations to acquire (*inter alia*) competence and self-determination, which are intrinsically linked to emotions of interest and enjoyment (Deci & Ryan, 1985). Ryan & Deci (2000) define motivation as to ‘be moved’ to do something and describe it as follows:

“…the doing of an activity for its inherent satisfaction rather than for some separable consequence. When intrinsically motivated a person is moved to act for the fun or challenge entailed rather than because of external prods, pressures, or rewards”.

(Ryan & Deci, 2000, p. 56).

According to these authors (and various others) motivation may differ not only in amount between individuals but also in its orientation, which depends on the underlying goals and attitudes that give rise to action. These goals can be classified as either intrinsic motivators (things that are done because they are enjoyable) or extrinsic motivators (things that are done to receive rewards). Intrinsic motivation is particularly interesting for educators since it can be a “natural wellspring” of learning (Ryan & Deci, 2000). A key intrinsic motivator, according to Pink (2010), is *mastery*, “the desire to get better and better at something that matters”, for which humans need to be engaged in order to put in sufficient effort. Pink’s reasoning is further supported by Greene, Miller,
Crowson, Duke & Akey (2004) who found that students’ perceptions of tasks, autonomy, mastery and evaluation are important for their degree of motivation in the classroom.

Conceptual Change

Within science education research a very influential and productive theme has emerged called conceptual change (Duit & Treagust, 2003), which leans on the basic assumptions of constructivism. Conceptual change is broadly defined as the process whereby individuals’ conceptions change over time (Posner, Strike, Hewson & Gertzog, 1982). Researchers concerned with this process attempt to elucidate how concepts change in content and organization. However, over time various perspectives of conceptual change and the significance of prior conceptions have been proposed, including fine-grained and misconception constructivism (Elby, 2000). Misconception constructivists (e.g. McCloskey, 1983; Strike & Posner, 1985) view conceptual change as a complete shift of conceptions, via a process in which old conceptions are not part of the material learners use while constructing new knowledge. In contrast, fine-grained constructivists (e.g. Smith III et al., 1994; Tirosh et al., 1998) consider conceptual change to involve the modification of humans’ intuitive generalizations into more sophisticated, united and coherent structures (Elby, 2000). Both intuitive and scientific understandings are part of the same group of conceptual resources and conceptual change is viewed as the reorganisation of these resources. The fine-grained constructivist view on conceptual change is held in this thesis.

The likelihood of a conceptual change occurring will also depend on the “status” of old concepts (Hewson & Hewson, 1984), which in turn is influenced by a person’s epistemological commitment, for example to generalizability. If a student’s existing conceptions have “high status” a new, conflicting, conception will not be accepted by the student until the status of the old conceptions is reduced, and in such cases the student must be provided with a credible reason for being unsatisfied with the old conception (Hewson 1992). This is in unity with the valid cues (explanations) our reasoning needs when addressing conflicts.
between intuitive expectations and encountered problems or situations as suggested by Kahneman (2012).

**Intuitions and Conceptual Conflicts**

In the science education literature a variety of terms are used to refer to students’ intuitive ideas about natural phenomena (Özmen, 2004). As sketched in Chapter 4, intuitive ideas could be a source of students’ difficulties in understanding science concepts. For example, Pedersen & Helldén (1994) have found that students construct their knowledge of animal and plant adaptations using both biological knowledge and their intuitive ideas about nature and that this can cause difficulties. Notably, even if intuitive ideas may be a source of student difficulties several studies indicate that using counter-intuitive examples can be beneficial for students’ learning, since they challenge habitual thoughts and intuitive expectations (Gordon, 1991; Lesser, 1998).

A key basis for conceptual change is the experience of a divergence between existing and new conceptions. Thus, creating conceptual conflicts has been promoted as a pedagogic strategy (Berlyne, 1965; Hewson & Hewson, 1984) that can (*inter alia*) lead to intellectual commitment from learners (McDermott, 1993). A conflict draws attention to a problem and increases the probability for students to consider a new and alternative view (Eylon & Linn, 1988). An effective means of initiating conceptual change is believed to be active learning. For example, in a review of the conceptual change literature Guzzetti (2000) concluded that reading and discussing refutational text is an effective way of changing students’ conceptions. Furthermore, through case studies, Nussbaum & Novick (1982) showed that conceptual conflict enhances accommodation of novel concepts. They also described an explicit strategy for initiating conceptual change concerning students’ difficulties in learning a particle model. The strategy has three parts: exposing preconceptions, creating a conceptual conflict and encouraging accommodation of the new concept(s).

Perkins (1999) suggests that qualitative teaching approaches can be used in the first part of this strategy, i.e. to expose students’ intuitive beliefs and interpretations. In the second part, counter-intuitive experiences are required, since they naturally generate conceptual conflicts, and when interpreting a
counter-intuitive phenomenon in an active and exploratory way students are confronted with the character of the focal phenomenon. Similar ideas have been proposed by Jacobson & Willensky (2006), who argue that pedagogical approaches for learning about complex systems should focus on the conceptual aspects of students’ learning as well on their beliefs and intuitions about the world. Lesser (1998) promotes appropriate use of counter-intuitive examples in statistics curricula and argues that they can not only challenge students’ intuitive beliefs, but also act as motivational factors, engaging them to create the prerequisites for deeper understanding. Gordon (1991) suggests that counter-intuitive examples are also beneficial in mathematics education, since they challenge habitual thoughts, gain attention and encourage learners to explore, reflect and reason. Numerous variables, both cognitive and affective (emotional) may be important for the final phase, accommodation of new concepts (Duit & Treagust, 2012; Pintrich & Schrauben, 1992), some of which are explored in the following sections.

Although conceptual conflicts are necessary for conceptual change they are not always sufficient. Guzzetti (2000) found that some students were only able to change their intuitive ideas after engaging in a discussion. Discussions require students to articulate and support their views and help students modify their incomplete and intuitive understandings of complex science concepts (Alvermann, Hynd & Qian, 1995). In addition, Eylon & Linn (1988) suggest that researcher (and teachers) should focus on both students’ prior knowledge and their reasoning.

Prior knowledge, Emotions and Conceptual Change

Research based on ‘classical’ conceptual change perspectives has focused on mental processes and has faced challenges in developing successful instructional strategies for facilitating learners’ conceptual change. Although the traditional view of conceptual change, as defined by Posner et al. (1982), acknowledges the importance of social and motivational/affective factors for the learning process the focus has been on what learning is, not what learning depends on. However, recently researchers have increasingly addressed the role of emotional factors in conceptual change (Duit & Treagust, 2003/2012, Pinrich, Marx & Boyle,
5. Prior Knowledge, Emotions and Conceptual Change

1993; Pintrich & Schrauben, 1992; Zembylas, 2005). Pintrich & Schrauben (1992) argue that motivational and emotional factors may facilitate or constrain conceptual change, while Pintrich et al. (1993) hold that interactions between the classroom context, motivation and cognition are important factors. They also suggest that when students encounter information that conflicts with what they already know, their beliefs about their ability to manage tasks, and thus self-efficacy, influence their confidence to handle the conflicts and change their conceptual understanding. It is further supported by D'Mello and Graesser (2012), who propose a model for the dynamics of affective states during problem-solving and claim that students become confused when they experience cognitive disequilibrium (facing new, unexpected, knowledge), which can lead to disengagement and boredom if they cannot progress to acceptance of the new knowledge. Further, Pintrich (1999) suggests that factors such as self-efficacy and confidence, autonomy, mastery, and personal relevance are mediators for the process of conceptual change, i.e. the incorporation of new conflicting knowledge with prior knowledge. Based on a review of the literature of conceptual change in psychology, science education and social sciences, Dole & Sinatra (1998) propose a model for cognitive reconstruction of knowledge, in which existing conceptions, motivation, plausibility and students’ level of metacognitive engagement are important and essential factors of conceptual change. Following these, and other, developments in conceptual change theory, Duit & Treagust (2012) hold that conceptual change is still a powerful framework for instructional design, but researchers need to pay equal attention to both cognitive and affective variables.

Guzzetti (2000) advocates that conflicts are effective since they are inherently interesting and the conflict cause students to question their intuitive ideas. If a new conception conflicts with a student’s existing conceptions, it can only become reasonable in the mind of the student if (s)he becomes unsatisfied with his/her old conception (Hewson, 1992). Scott, Asoko, & Driver (1991) describe how any conflict-based strategy for enabling conceptual change are dependent on students willingness and ability of students to recognise an solve the conflict. A presented conflict is used as a motivational factor for searching for a better explanation (Clement, 1987; Nussbaum & Novick, 1982; Scott et al.,
For example, Schönborn, Haglund & Xie (2012) found that students were emotionally charged when encountering a conflict while using thermoimaging in conceptualising heat transfer. Even though their students did not succeed to resolve the conflict, they propose that affective factors may be an important factor for successful conceptual change. Motivational and emotional factors may facilitate or constrain students’ conceptual change (Pintrich & Schrauben, 1992).
5. Prior Knowledge, Emotions and Conceptual Change
6. Aims and Research Questions

Understanding the molecular world is essential for explaining countless phenomena. However, molecular processes are difficult to assess and students have no direct experience of them. Thus, representations are essential conceptual tools for making molecular processes visible and understandable. The overall objective of this thesis is to evaluate whether (and if so how) representations can support students’ conceptual understanding of molecular processes. I address these issues in this section, with illuminations provided by results presented in the appended papers, focusing specifically on the following four research questions (the first two theoretically grounded in the scientific literature, and the other two empirically grounded and concerned with students’ conceptual understanding).

1. What facets of the process of self-assembly can be identified from the science literature as important for a conceptual understanding of self-assembly?

2. What aspects of self-assembly can be identified from the literature as counter-intuitive?

3. What differences in students’ conceptual understanding can be observed after interactions with representations?
   a. How do students’ interactions with the tangible model or image, encountered together with peers, influence students’ conceptual understanding of the identified facets of self-assembly?
   b. How does students’ use of metaphors, generated in interaction with an animation and peers, influence their conceptual understanding of the reversibility of ATP synthesis?
6. Aim and Research Questions

4. How do counter-intuitive aspects of self-assembly influence students’ conceptual understanding of the process?
   
a. Do the identified counter-intuitive aspects of self-assembly generate a conceptual conflict within students?
   
b. How can we facilitate students’ conceptual change of self-assembly?
   
c. Do the studies provide any evidence of relationships between students’ emotions and the process of conceptual change?

The four questions are related to learning in molecular life science and the constraints in this domain on students’ learning. By inter-relating these questions we can disentangle how different factors influence students’ conceptual understanding of molecular processes such as self-assembly and ATP synthesis, thus acquiring a richer understanding of students’ learning of molecular processes through representations. However, research questions three and four could also be of more general interest. Question three could be of interest to those concerned with how students learn and interpret representations in a collaborative learning environment, a setting we frequently encounter in education. Question four concerns the relation between students’ intuitions and new knowledge, and (hence) possible ways to facilitate students’ accommodation (conceptual change) of new conflicting knowledge. The appended papers provide illumination and information about various aspects of the research questions, thus contributing to the results and discussion of the thesis as a whole. Research questions one, two, three and four are addressed with illuminations from both previous literature and Papers I and II, Paper III, Papers I, II and IV, and Papers II and III, respectively.
This chapter describes the methodology and methods applied in the studies described in the appended papers. First, I present the purposes of qualitative and quantitative methods, how they are generally used, and how the chosen methods relate to my theoretical framework. This general introduction to methodology is followed by sections describing the research design, samples, context and instruments used. The chapter ends with a section describing the qualitative and quantitative analyses and a discussion of the validity, reliability, generalization, and limitations of the applied methods, and ethical considerations. For more detailed accounts of methodological issues and methods used in each study, see the respective papers.

**Qualitative and Quantitative Research**

Both qualitative and quantitative research strategies have been applied in the papers, but mainly qualitative strategies. Quantitative research refers to the collection of numerical (quantitative) data, which are usually deductively analysed to test (or develop) theories of causal nature, i.e. to determine explanatory, generally mathematically expressed, relations between studied objects or processes (Bryman, 2002; Robson, 2002). Quantitative research designs are generally quite fixed and follow a range of discrete steps. If the data are rigorously collected, advantages of quantitative research include the ability to measure small differences (if the instruments used are sufficiently sensitive), consistency of the measurements (if the instruments are sufficiently precise, and the studied systems are sufficiently tightly controlled and stable), and generalizable of the results to a wider population (if the studied samples are
7. Methodology and Methods

sufficiently representative) (Bryman, 2002). However, quantitative methods have been criticized for sometimes providing a somewhat false feeling of correctness of the measurements, particularly for examining social processes and effects of human factors (Bryman, 2002). This is partly because it has not (yet) been possible to develop sufficiently sensitive, precise instruments to quantify them robustly and/or unfeasibly broad investigations would be required to cover the massive ranges of variations in confounding variables encountered in social interactions. In qualitative research of phenomena with a strong social or human element, such as the cognitive processes addressed in this thesis there are diverse approaches, but they have some common qualities. As expressed by Gibbs (2007, p. x):

Qualitative research is intended to approach the world ‘out there’… and to understand, describe and sometimes explain social phenomena ‘from the inside’ in a number of different ways.

This can be done by analysing interactions and communications of individuals or groups in order to explore how people construct the world around them. In addition, Bryman (2002) noted that qualitative researchers focus more on words than quantifiable variables, often use an inductive approach when considering the relationship between theory and research, and generally focus on how individuals perceive and interpret their social reality. In addition, in qualitative research the researcher is an important part of the process since s/he is intimately involved in the data collection and brings experiences from the field under study (Gibbs, 2007).
7. Methodology and Methods

Research Design

Robson (2002) calls qualitative designs flexible, as they frequently develop and evolve as the data collection proceeds substantially more than quantitative designs. However, sometimes it is valuable to apply a mixed-methods approach, combining qualitative and quantitative methods, for several reasons, some of which are presented in the following bullet list:

- Triangulation, i.e. to check the results obtained from the quantitative analysis by comparing them to those obtained from the qualitative analysis;
- Qualitative data can be used to facilitate the fixed quantitative design by providing information about the context and participants;
- Provide a more complete picture of the studied phenomena;
- Include both researchers’ and participants’ perspectives, since a fixed design is usually based on the researchers’ perspectives while flexible designs usually capture the participants’ perspectives better;
- Facilitate interpretations, since qualitative analyses may complement quantitative analyses by providing possible explanations for identified relationships between measured variables.

(Robson, 2002, p. 372)

The designs of the studies reported in Paper I-IV and the types of empirical data collected in them are shown in Figure 1. In Papers I and II a mixed-method approach was applied. In both of these studies a true, fixed (quantitative) experimental method (Robson, 2002) was employed: pre-test post-test two treatment comparison, in which students were randomly allocated to one of two intervention groups. This was combined with flexible (qualitative) elements, by analysing data through the use of open-ended questions in the pre- and post-tests and audio-recorded interviews. In contrast, in Papers III and IV a strictly flexible (qualitative) research design was applied, analysing data in the form of transcripts from audio recorded interviews and group discussions. These papers started with a problem or idea that the authors wished to understand; a feature of an investigation with a good flexible design (Robson, 2002), in which relationships and comparisons only emerge later during the research process.
Figure 1: An overview of the designs of the studies reported in Papers I-IV, and the types of empirical data collected in them. Boxes with bold black and borders indicate analysed quantitative and qualitative data.

Moreover, the approach applied in Paper I was extended in Paper II to include a teaching learning-sequence (TLS), a more authentic learning environment. Such sequences are frequently used in science education research to examine effects of teaching or pedagogic interventions on students’ learning at either a micro-level (e.g. a single session) or intermediary level (e.g. a single topic sequence) (Méheut & Psillos, 2004). The TLS included an introductory session and follow-up lecture, for more information see Paper I.

Theoretical Perspectives and Choice of Methods

The holistic theoretical framework of the studies and this thesis provided the foundations for the methods used in the four studies and guided our thinking regarding their design. We are searching for the processes that underlay events in complex social situations (Kozma, 1994). The framework, described in detail above, incorporates elements of several theoretical perspectives, allowing us to
address different questions resting on different assumptions (Zembylas, 2005). Relations between the theoretical perspectives and chosen methods are illustrated in Table 4.

Table 4: Relations between the theoretical perspectives and chosen methods.

<table>
<thead>
<tr>
<th>Some selected characteristics</th>
<th>Choice of methods</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distributed Cognition</strong></td>
<td></td>
</tr>
<tr>
<td><strong>System Perspective</strong></td>
<td></td>
</tr>
<tr>
<td>• Human action through activity – activity is shaped and enabled by resources that are distributed throughout people, the environment, and culture.</td>
<td>• Group discussions</td>
</tr>
<tr>
<td>• The human body is part of the cognitive system, through which we relate to the environment (the material world).</td>
<td>• Use of external representations as focus instruments</td>
</tr>
<tr>
<td><strong>Constructivism</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Individual Perspective</strong></td>
<td></td>
</tr>
<tr>
<td>• Personal discovery</td>
<td>• Part of students’ ordinary teaching (TLS)</td>
</tr>
<tr>
<td>• Realistic (authentic) situations</td>
<td>• Pre- and Post-tests</td>
</tr>
<tr>
<td>• Active and self-regulated learners</td>
<td>• Interviews</td>
</tr>
<tr>
<td><strong>Social Constructivism</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Individual and Social Perspective</strong></td>
<td></td>
</tr>
<tr>
<td>• Discovery of shared and personal meanings</td>
<td>• Group discussions</td>
</tr>
<tr>
<td>• Collaborative learning and problem-solving</td>
<td>• Researcher-facilitated group discussions to promote scaffolding</td>
</tr>
<tr>
<td>• Receive different perspectives through language</td>
<td></td>
</tr>
<tr>
<td>• Scaffolding as an instructional strategy</td>
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</tbody>
</table>

According to constructivist ideas, all our expressions and actions are informed, activated or filtered by our constructs and ideas about the world (Gibbs, 2007), which result from individuals’ efforts to make sense of their experiences. Thus, statements in the qualitative data reflect conceptions of the participating individuals (both the researchers and respondents), which were created from their constructions of the world (Gibbs, 2007). In the eyes of a constructivist, statements are equivalent to objective data, such as direct observations of some
7. Methodology and Methods

phenomenon in quantitative research. The qualitative data thus reflect the interplay between the researchers’ and respondents’ constructions (Gibbs, 2007). According to social constructivism, learners construct knowledge both individually and in a socially shared context. Thus, knowledge is constructed through authentic projects where students discuss and discover phenomena (Hung, 2001) and the teacher acts as a facilitator for support and scaffolding. The context in which learning takes place is also important (McMahon, 1997).

In order to gain insights into how the students included in the studies constructed their concepts related to the focal subject matter, self-assembly and ATP synthesis, the qualitative analysis was based on the recorded interactions and communications among the students and between the students and interviewers. In qualitative research there is a strong focus on studying the nature of phenomena. Thus, factors and explanations should be viewed in the light of the wider context (Gibbs, 2007). This corresponds well to the distributed cognition view, that cognition is distributed among individuals, the environment and culture, rather than solely in individuals’ private mental processes, so external representations, internal representations and language are all parts of the cognitive system. Following suggestions from Allwood (1983), “that we can think without speaking but not speak without thinking”, we may conclude that speech mirrors some of the mental representations of individuals, and that qualitative analysis of speech provides meaningful insights into their cognitive processes. Therefore, some parts of individuals’ thought processes interact with, and reflect, elements of the social and material context.

Samples and Contexts

The empirical data reported in Paper I-IV was collected in three different studies (see Figure 2). Paper I, II, III and IV included empirical data from Study 1, Study 2, Studies 1 and 2, and Study 3, respectively.
7. Methodology and Methods

![Diagram showing the relationship between Paper I, Paper II, Paper III, and Paper IV with Study 1, Study 2, and Study 3]

**Figure 2:** An overview of the empirical data reported in Paper I-IV that was collected in three studies with different sample and contexts.

The empirical data collected in Study 1 included expressions of 32 Swedish university students (23 females, 9 males) during practical group exercises (group discussions) focusing on the self-assembly process, which were integrated into part of a biochemistry course, and the students’ scores in written pre- and post-tests. The students’ understanding of the process was then explored by assessing their expressions, and answers in the tests, in relation to key facets of the process. The participating students, all of whom had completed an introductory biochemistry course, were divided into six groups. Three groups used a three-dimensional tangible model as a focus instrument and the other three groups used a textbook image as focus instrument. The tangible model and textbook image are described below and in Paper I.

The sample in Study 2 included 20 third-year biochemistry students (12 females, 8 males) registered for a protein structure and function course at a South African university. This study was designed as a teaching-learning sequence (TLS) (Méheut & Psillos, 2004), including an introduction, a group tutorial, and a follow-up lecture. The introduction was framed to present and allow the participants to become familiar with the context of self-assembly. The tangible model was used as a focus instrument in three group discussions, with six to seven students in each group. Five individual semi-structured interviews was performed approximately 10 days after the TLS. Written pre- and post-test scores were also collected.

In Study 3 the empirical data collected were expressions of 43 Swedish university students (20 females, 23 males) studying on the medical biology, biology or the teacher education programme. The students were recorded as they tried to make meaning of ATP synthesis while interacting with an animation.
Methodology and Methods

(described below) during six group discussions. The students had very limited or no knowledge of ATP synthesis, although they had all successfully completed basic courses in molecular biology and chemistry. However, before the data collection session they were given the opportunity to individually interact with the animation to familiarise them with the learning environment and ensure that they had similar levels of prior knowledge (individual phase). In addition, the designer of the animation was interviewed, in a structured interview that included an introduction, then covered the background of the commissioning of the animation, the designer’s intentions, the semiotics associated with the design, and the animator’s thoughts about students’ interpretations of the animation.

External Representations Used in Studies 1-3

The Tangible Model

The interactive tangible model (Olson et al., 2007) used in Studies 1 and 2 represents the assembly of a poliovirus capsid (see Figure 3A), a spherical shell that self-assembles from identical protein subunits and encloses the viral genome, in this case RNA. The model is composed of 12 pieces of plastic, representing the capsid subunits, with magnets along the edges that allow them to attach to and detach from each other, in a transparent container. The container is shaken to activate the self-assembly process, and the model readily shows the dynamics of the process and its progression over time. The process is unpredictable but typically finishes in between one to five minutes. The model (used with permission from Prof. Arthur Olson, Scripps Institute, La Jolla, with whom we collaborate) was introduced as an external representation of virus assembly, stressing that it is a model representing a molecular process.

The Textbook Image

The image used in Study 1 was obtained from the biochemistry textbook Molecular Biology of the Cell by Alberts et al. (2008) and illustrates the structure and assembly of a spherical virus called the tomato bushy stunt virus (TBSV; see Figure 3B). The image depicts the self-assembly of virus capsid subunits around the genome of the virus. One protein subunit is shown in some structural detail while the others are represented schematically. Different colours are used to
emphasize that identical subunits may have slightly different environments. The structure of the assembled capsid has been determined by x-ray diffraction (Alberts et al., 2008).

*Figure 3A:* The tangible model that mimics the process of self-assembly of a poliovirus capsid.

*Figure 3B:* The image of the process of self-assembly of a tomato bushy stunt virus capsid (Alberts et al., 2008)
7. Methodology and Methods

The Animation

The animation used in Study 3 is part of the educational material linked to the book *Molecular Biology of the Cell* (Alberts et al., 2002) and illustrates the formation of ATP catalysed by the enzyme ATP synthase and the cellular context of its formation (see Figure 4). The animation has four parts, but only the first two were used in the study. Part 1 provides an overview of ATP synthesis by schematically illustrating the protein ATP synthase and the reactants, while part 2 shows the dynamic tertiary structure of ATP synthase, based on crystallographic data, in the form of a ribbon model structure. These sequences include the movement of the protein’s “rotor shaft”, which induces dynamic conformational changes that are essential for the synthesis of ATP (or more strictly phosphorylation of ADP).

![Figure 4](image-url)

*Figure 4:* A snapshot of the animation showing the catalysis of ATP synthesis by presenting the protein ATP-synthase.
7. Methodology and Methods

Instruments

Interviews
Like all methods, interviewing has both advantages and disadvantages, thus it can be fruitfully combined with other methods (Robson, 2002). Generally, interviews are flexible, and the face-to-face interaction allows the interviewer to track interesting responses and see non-verbal cues that may facilitate interpretation of verbal responses (Robson, 2002). Potentially, as mentioned, they can also provide researchers with rich information. However, this is subject to the interviewer’s skills and experience of interviewing. A further major concern associated with interviews as a research method is the lack of standardization, which is linked to doubts about the reliability of the collected data, and possible biases (Robson, 2002). Notably, informants have a tendency to give responses that are influenced by their understanding of what is socially accepted and/or please (or provoke) the interviewer (Bryman, 2002). It is also important to remember that interviews are learning situations for informants (students in this case) and should preferably be placed at the end of a data collection sequence. Interviews were used to collect data in Studies 2 and 3 and the analysis of the interviews are reported in Papers II-IV. The interviews were semi-structured and the interviewer used an interview guide (see Appendixes 1 and 2), and they were audio-recorded and transcribed verbatim.

Group Discussions
Like interviews, group discussions are commonly used in qualitative research. The focus is generally on how the informants understand a certain subject. Thus, the dialogue is generally semi-structured to allow the participants to express their views about the subject, while the discussion facilitator organises the discussion, but remains rather passive (Bryman, 2002). Group discussions were used to collect data in all three studies, although the data acquired in these discussions were not explicitly analysed in Papers I and II. All of the discussions were based on a focus instrument (the tangible model, textbook image or animation described above), and discussion guidelines was used for guidance and scaffolding
7. Methodology and Methods

(see Appendixes 3 and 4). The discussions were audio-recorded and transcribed verbatim.

Individual interviews generally have a traditional question-and-answer format. It is difficult to maintain such a structure in group discussions, but this may be advantageous as participants are stimulated by others’ thoughts and comments (Robson, 2002). Thus, they may argue and even change opinions, depending on how the discussion develops. From a research perspective this situation is desirable, since it provides a natural and realistic portrayal of people’s expressed thoughts and understanding of the focal topic (Bryman, 2002). In addition, extreme views tend to be ruled out (Robson, 2002). However, the method is more time consuming than individual interviews and may be more complicated to arrange. Further, group dynamics may have significant effects on the expressed thoughts, since (for example) eloquent people tend to be more active than reserved people in groups (Bryman, 2002). Therefore, these types of discussions need to be well managed (Robson, 2002).

There is also evidence that group discussions and activities are valuable in pedagogic practice, as well as in research. Notably, a recent review of classroom-based science education research concludes that group work and peer discussion are important strategies for successful science teaching since they appear to develop students’ cognitive and metacognitive skills and promote positive attitudes among students (Coll, France and Taylor, 2005) and collaborative learning can lead to positive attitudes towards science (Matthews, Kilbey, Doneghan, & Harrison, 2002; Springer, Stanne & Donovan, 1999). In addition, collaborative learning processes may activate students’ prior knowledge, which, in turn, facilitates the processing of new knowledge (Schmidt & Moust, 1998).

Pre- and Post-tests

Pre- and post-tests are commonly used in behavioural and social science in order to compare groups or effects of treatments or interventions. They were used as instruments in Studies 1 and 2 to obtain both quantitative data (from Likert-scale items) and qualitative data (from open-ended questions). In Study 1 the participants were divided into two experimental groups for group discussions based on either the tangible model or the image, while in Study 2 the group
7. Methodology and Methods

discussion was part of a teaching-learning sequence and was based solely on the tangible model. Pre- and post-test papers were distributed before and after the intervention, respectively, in both studies.

The advantages of using pre-tests are that they provide controls to check that the random allocation of participants has resulted in equivalent groups and give the researcher an opportunity to use differences between pre- and post-test scores to measure effects of the treatment(s) (Robson, 2002). However, there are also some disadvantages, notably a pre-test may influence participants’ answers in the post-test (Robson, 2002) and questions related to the internal and external validity of the results (Dimitrov & Rumrill, 2003), as further discussed in the Discussion of Methods section below.

Quantitative analysis

The term analysis refers to the process of separating an entire object or phenomenon of some kind into its constituent parts and investigating their relations to gain a better understanding of it. In quantitative research the analytical methodology must be appropriate for the nature of the data, including the size and characteristics of the samples (Bryman, 2002). Ideally, the results should be statistically significant, or have sufficient statistical power to demonstrate with confidence the validity or falseness of a hypothesis and/or generalize findings obtained for a randomly selected sample to a wider population from which it was drawn. Analysis of Variance (ANOVA) is a widely used method for exploring effects of specific independent variables (such as treatments) on scores, values or observations (Langdridge, 2002). Papers I and II both included quantitative analysis of empirical data obtained from pre- and post-tests, using the SPSS software package (version 19). In Paper I changes in students’ knowledge of self-assembly were explored by [2×2] mixed ANOVA to assess both differences between groups of students exposed to the tangible model and textbook image external representation and within-group differences in pre- and post-test scores. In Paper II changes in students’ understanding of the facet of self-assembly were explored by using paired sample t-tests.
7. Methodology and Methods

Qualitative analysis

A key objective of qualitative research on social or human phenomena is to be able to interpret the data and see it from the perspective of the respondents (Gibbs, 2007). The analysis is merged with the collection of data, thus qualitative strategies are quite flexible, the data analysis begins in the field, and research questions can be modified as the study proceeds. Large amounts of multiple kinds of data are often collected, which are often coded to facilitate management and organisation of the information. The analysis also includes linking the conclusions to theories and knowledge in the form of constructs (Robson, 2002), thus theoretical and interpretative notes are often appended to the codes, and other analytical documents. Qualitative data were collected and treated in this manner in Papers I-IV. The analysis involved “office-processes” (sorting, retrieving, indexing and handling) and thereafter interpreting the results to draw conclusions (Gibbs, 2007).

Data Handling

As mentioned above, researchers need to use so-called “office-procedures” in qualitative analysis, including sorting, retrieving, indexing and processing the large volumes of data generally acquired (Gibbs, 2007). The procedures applied in the studies this thesis is based upon included verbatim transcription of audio recordings of interviews and group discussions, either by the researchers themselves or by other appropriate personnel. As transcription involves transferring information from one medium to another the process inevitably involves some degree of interpretation, raising issues related to accuracy (Gibbs, 2007). For this reason the entire recorded conversations were transcribed, to ensure that nothing in the conversations was missed. All participants were also anonymized to ensure confidentiality.

Data Interpretation

In qualitative analysis, as in quantitative analysis, the researcher is concerned with finding patterns in the acquired data and explaining them. In terms of “traditional” content analysis of communications this involves “making
7. Methodology and Methods

inferences by objectively and systematically identifying specified characteristics of messages” (Holsti, 1969). Such characteristics, or themes (or codes related to themes), emerge from acquired empirical data that are filtered through the researcher’s theoretical understanding of the scientific content (Ryan & Bernard, 2003). Gibbs (2007) describes two ways of “explaining” patterns: inductive and deductive. An inductive explanation involves “the generation and justification of a general explanation based on the accumulation of lots of particular, but similar, circumstances” (Gibbs, 2007, p.4). In contrast, deductive explanation refers to the explanation of “a particular situation” by reasoning (deduction) “from a general statement about the circumstances” (Gibbs, 2007, p.5). The latter is common in quantitative research when a hypothesis is construed and tested against observations.

Steps in the analysis initially entailed pawing, also known as eyeballing, through the text several times to get a sense of the material and search for key components and patterns (Ryan & Bernard, 2003). The analysis in all four papers appended to this thesis then followed a model for qualitative content analysis (Graneheim & Lundman, 2004) in order to elucidate the depth and character of students’ learning. In Papers I-III the content analysis was systematic and performed in two rounds (Kreuger & Casey, 2000): one inductive (Abell & Smith, 1994) and one deductive. In Paper IV, inductive analysis of the students’ use of metaphors in the group discussion transcripts was combined with deductive analysis of the interview transcript. For further details of the qualitative analysis in the studies see the methods and analysis sections in the respective papers.

Discussion of methods

In largely quantitative research fields there is wide, perhaps universal, acceptance of the importance of considering the reliability, validity and generalizability of results, and numerous statistical techniques have been developed for testing these features of acquired datasets. In contrast, the applicability of such techniques to qualitative research has been debated, since a naturalistic approach is applied that yields results that are not readily amenable to statistical evaluations (Golafshani, 2003). However, triangulation and several other approaches can be applied to
7. Methodology and Methods

assess the reliability and validity of results obtained from both quantitative and qualitative research (Golafshani, 2003). The following sections discuss and highlight these issues in relation to the research this thesis is based upon.

Reliability

According to Gibbs (2007, p. 91), “results are reliable if they are consistent across repeated investigations in different circumstances with different investigators”. Reliability in this context refers to the stability or consistency of the findings, rather than their accuracy, veracity or generalizability (Robson, 2002). Throughout the studies this thesis is based upon my co-authors and I used several strategies for improving the reliability of the qualitative results. Firstly, as themes/codes were identified in the qualitative analyses, memos were constructed to use as constant comparison tools in order to avoid code drifting and keep the themes/codes constant during the whole categorisation process (Gibbs, 2007). Secondly, we used a code cross-checking method to “minimize researcher’s bias and get a measure of the reliability of coding” (Gibbs, 2007 p. 99-100). For this purpose, two or more coders examined all the transcripts from the group discussions and interviews, then the results of their analysis and interpretations were compared. In most cases, the categories identified by different coders were the same or similar, and in the few cases where assessments disagreed a consensus was negotiated. In addition, in the quantitative analysis in Paper I we used the Kuder-Richardson Formula 20 (KR-20) test to assess the internal consistency of the data related to dichotomous variables (those for which there were only two categories), rather than Cronbach’s α test, which is used for continuous (non-dichotomous) variables. In this study we analysed both students’ knowledge of self-assembly and their confidence in their answers. However, since we found that confidence scores for individuals that had been in the same group discussion were correlated, i.e. a significant intraclass correlation coefficient (Kenny, Kashy & Bolger, 1998), the confidence data were not analysed further. In contrast, no correlation with groups was found for the knowledge scores.
7. Methodology and Methods

Validity

According to Gibbs (2007, p. 91), “results are valid if the explanations are really true or accurate and correctly capture what is actually happening.” However, there are two major classes of validity for results obtained from quantitative research: internal and external. Internal validity refers to the veracity of a proposed causal relationship (i.e. that observed changes are not due to some other variable) and external validity to the degree to which results are generalizable beyond the given study (Bryman, 2002). External validity is further discussed in the next section (Generalizability).

One way to assess the validity of findings is to use triangulation. Simply, this refers to viewing acquired material from different perspectives in order to obtain a more accurate, or complete, understanding of variables related to participants or the context of a study, or any other investigated objects or variables. It can be applied on several different levels, such as: (i) samples or datasets, (ii) investigators, or (iii) research theories (Gibbs, 2007). We can also triangulate findings by comparing results obtained using quantitative and qualitative methods (Bryman, 2002). Triangulation, can for, example be useful for revealing mistakes, support judgements of the relative likelihood of results, and to assess the consistency of informants’ statements throughout a study.

Triangulation was used in all four papers to assess the consistency of different investigators’ analyses and interpretations of the data, after two or more researchers initially analysed the material independently. In addition, results from Papers I and II were triangulated by comparing findings obtained using quantitative and qualitative methods. Finally, triangulation can be applied to assess the validity of the overall findings from the four studies by comparing the respective data sets and contexts.

Other strategies were also employed to assess the validity of the qualitative results. In Paper IV the transcript of the interview with the animator was validated through transcription checking (Gibbs, 2007), i.e. we gave the animator the transcript to check, in an attempt to avoid mistakes in our interpretation of his answers to our questions. However, it should be noted that although this (and all the other) transcripts were transcribed verbatim, information is transferred from one medium to another in any transcription and there is always a possibility
of misinterpretations. In some cases, as a further measure to minimise misinterpretation, the entire analysis was reviewed and discussed by a larger research group consisting of people with different backgrounds, for example molecular life sciences, protein chemistry, biochemistry, visual learning and communication, educational sciences or media technology.

**Generalizability**

According to Gibbs (2007, p. 91), “results are generalizable if they are true for a wide (but specified) range of circumstances beyond those studied in the particular research”. The range of circumstances mentioned by Gibbs in this quotation could include (*inter alia*) other contexts, situations or participants than those included in a given study (Robson, 2002). According to Larsson (2009), qualitative data can be generalized through context similarity, provided the research context is known and sufficiently well described. For this reason we aimed to describe the contexts of the studies in sufficient detail in the methodology sections of the respective papers to enable a reader to compare them adequately to other contexts. Another strategy to obtain general findings from qualitative research is through recognition of patterns, although this is dependent on the reader’s ability to recognise patterns in pieces of research that can assist interpretations in other situations, processes or phenomena (Larsson, 2009). I believe that some patterns in the qualitative data obtained from the studies underlying this thesis could indeed be recognised by readers and applied to other situations and to other phenomena, but of course this is a subjective judgement. Another risk in qualitative research is to overgeneralize the results by “cherry-picking” quotations that are striking and interesting, but may be untypical examples of the material as a whole (Gibbs, 2007). To guard against this, in Paper III we also reported on the existence of observations throughout the group discussions for certain classes of observations. Finally, in the quantitative analyses in Papers I and II we used a mixed-method approach and randomized samples. Therefore, it is possible to discuss the possibility to generalize these results to a wider population more rigorously.
7. Methodology and Methods

Limitations

No research can provide absolutely true information about any phenomenon, it can only offer insights or indications of varying plausibility. This may appear discouraging, but rather it suggests that readers should be critical and carefully assess the reliability, validity and generalizability of presented results (Gibbs, 2007) and the overall plausibility of conclusions (Jensen, 2002). As described above, various steps were taken to maximise these characteristics of the findings in Papers I-IV, but inevitably the research had several limitations, which should be discussed.

One set of limitations was inevitably associated with the settings and the aim to obtain high internal validity. This requires tightly controlled settings, with minimal influence of confounding factors, in order for instance to rigorously test hypotheses about putatively causal relationships between variables. However, learning is complex and occurs in complex situations, thus as we tighten control of the settings to increase internal validity we inevitably decrease the generalizability of the study (external validity) (Robson, 2002). Therefore, in Papers I-IV we attempted to achieve a balance between controlled and authentic settings in order to avoid excessively compromising either internal or external validity. We also applied several procedures, such as triangulation, to validate the results as much as possible, and avoid drawing incorrect conclusions about relationships between the studied variables. Notably, to minimize a common limitation of quantitative research — that it yields a fixed portrait of a social reality, which does not consider the uniqueness of the individuals involved in the situation (Bryman, 2002; Cohen, Manion & Morrison, 2007) — the quantitative analyses were complemented with qualitative analyses, thereby providing more in-depth knowledge of the character of students’ learning.

Two other limitations are that the samples of students were rather small, and restricted to students attending two universities, one in Sweden and one in South Africa. This inevitably restricts the ability to make robust generalizations. However, the similarities across different groups of students in the studies indicate that we can at least speculatively extend the findings to a wider perspective. In addition, following the claims made by Larsson (2009) concerning generalizability of qualitative data, mentioned above, we have in the
7. Methodology and Methods

 appended papers aimed at providing a rich descriptive presentation of the qualitative findings to assist readers to recognize patterns in pieces of the research that can assist interpretations in other situations, of other processes or phenomena.

Moreover, Gibbs (2007) stresses that qualitative research is mainly based on text and that the transfer of information from one medium to another, for example from audio recordings to transcripts or field notes to descriptions, involves interpretations. The inevitable simplification that occurs when describing complex social situations in text is another major concern in qualitative research, which we tried to meet through methods such as careful transcription and transcription checking. Another potential problem was participant bias, i.e. participants potentially giving responses to please (or provoke) the researchers or teachers involved in the research. Participant bias can compromise validity, since we cannot be certain whether the results reflect genuine, or biased, short-term effects (Robson, 2002). In addition, the students were introduced to new, perhaps exciting, external representations in all the studies, which may have influenced their attitude towards the situation and account for some of the detected effects. Moreover, some (or all) of the empirical data in Papers II and III were collected in a South African context, where some of the participants said that peer and group discussions in the classroom were normally quite rare and they expressed positive attitudes towards this form of teaching. Aspects such as these may also have biased students’ attitudes in favour the intervention. Furthermore, qualitative analysis is inevitably guided and framed by the researchers’ pre-existing ideas and they are often checking hunches, hoping to find certain results (Gibbs, 2007), thus researchers may be biased by favouring particular theories or the desire to validate a hunch. The analyses presented in the appended papers may also have been biased in this way, although we attempted to minimise this risk by using methods such as constant comparison and code cross-checking.

There are also possible sources of inaccuracies connected to interviews, for example a respondent may misunderstand a question, remember incorrectly, or be influenced by the way the interviewer poses a question (Bryman, 2002). In addition, the extent to which it is appropriate to provide participants freedom in
7. Methodology and Methods

A group discussion arranged to pose certain questions is not clear (Bryman, 2002). In the studies we used a discussion facilitator who remained rather passive during the discussions, but provided some structure and scaffolding. However, we have no way of knowing whether or not the arrangement was optimal.

Ethical Considerations

There are several standard ethical guidelines regarding the treatment of participants that should be followed in any educational research. The participants should be informed about the types of data that will be collected, exactly what will happen to them, and how the material will be used and handled after the study. It is important for participants to be aware that they have the right not to participate in the inquiry (Robson, 2002), and that they can withdraw at any time (Gibbs, 2007). If they do, data that have been collected concerning them must be destroyed or returned to them. Moreover, individuals must be protected and the researcher must make sure to keep the data confidential (Robson, 2002), especially in qualitative research since qualitative data are often very personal, in contrast to quantitative research where individuals are often hidden in statistics (Gibbs, 2007). Since it can sometimes be easy to identify specific individuals when reporting direct quotations it is also important to anonymise transcripts very carefully (Gibbs, 2007). In all four of the studies this thesis is based upon these standard ethical guidelines for educational research were followed, we did everything possible to make the participants feel safe and comfortable, and they all completed a written consent form prior to the data collection.

Ethical standards were also followed when reporting the research, regarding misrepresentation, plagiarism and assistance from others (Robson, 2002). The data and findings have been presented honestly and truthfully, without fabricating results, pretending to have done something that we have not done, or exaggerating the significance of the results. In the papers appended to this thesis my colleagues and I have strived to be honest and truthful. In addition, the contribution of each of the authors of each appended paper is reported in the List of Papers earlier in this thesis.
7. Methodology and Methods
8. Summary of the Results of the Papers

8. Summary of Results

In the following section I summarize the most important results and outcome reported in each Paper, for further details, please see the respective Papers.

Paper I

The analysis of the qualitative data presented in Paper I indicated that students were unfamiliar with self-assembly prior to the study. Their answers to the open-ended items in the pre-test did not include any explanation of self-assembly; they were unable to identify the relevant concepts and verbalize meaningful connections between them. However, quantitative analysis of their responses to the closed items showed that participation in the group discussion improved their scores from pre- to post-test, regardless of the intervention (use of the tangible model or textbook image as a focus instrument), and there was no significant between-intervention difference in this respect. Students of both intervention sets also significantly more frequently included descriptions of four facets of self-assembly (random molecular collisions, reversibility, error-correction and structural complementarity) in their post-test responses to the open-ended questions than in their pre-test responses. However the frequencies were higher among the responses of the students who interacted with the tangible model, although the differences in frequencies were very minor for the facets differential stability and influence of temperature (see Table 3 in Paper I).

Moreover, the qualitative analysis of the responses to the open-ended questions in the post-test revealed that students exposed to the tangible model provided more multi-faceted and complex responses than the students exposed to the textbook image, indicating that they may have developed deeper
understanding, which was not detected in the quantitative analysis. The qualitative difference in the two sets of students’ responses could be explained by the differences in how the external representations convey relevant aspects of the learning content. For example, the dynamic properties, related to movement and randomness, are more clearly represented in the tangible model. Hence, the tangible model particularly support students’ understanding of the random nature of molecular interactions.

In summary, the study showed that we can support students’ learning about certain facets of molecular self-assembly by letting them participate in a group discussion, interacting with peers and an external representation. Moreover, differences in students’ answers could be correlated with how the external representations conveyed relevant aspects of the learning content. In particular, the tangible model supported students’ understanding of the facet random molecular collisions. The results also indicate a need for closer investigation of the interactive learning processes that occur during group discussions.

**Paper II**

As in Paper I, in Paper II the students did not refer to any of the facets in their pre-test responses, indicating that they had little or no prior knowledge of the process. Furthermore, all of the interviewed students said that they had not thought about the process prior to the TLS and that they had taken it for granted. In the quantitative analysis of the empirical data we found a significant improvement in students’ scores from pre- to post-tests for items related to the facets random molecular collisions, differential stability and error-correction, but no significant differences in their pre-and post-test scores for items related to reversibility or influence of temperature. The results from the qualitative analysis of their responses to open-ended items in the post-test showed that most of the students correctly included random collisions between subunits in their descriptions of the process. In addition, half of the students made references to differential stability, error-correction and influence of temperature in their accounts. In contrast to the other facets, reversibility was only included in the post-test responses of a few students.
8. Summary of the Results of the Papers

In addition, a few difficulties were revealed during the data analysis. Some concerned the facet *influence of temperature*, for instance a student claimed that an increase in temperature will result in more errors, because subunits will move faster and therefore come together in the wrong way. This view is contradicted by the properties of the tangible model. Despite some pre-knowledge of the effect of temperature on the movement of molecules, the students seemed to have difficulties integrating the *influence of temperature* in their reasoning about the self-assembly process. The most striking learning gains were found for the facet *random molecular collisions*, although some students tried to apply generic “drivers” to explain the process.

In summary, the quantitative and qualitative findings provide complementary evidence for the success of the TLS in promoting understanding and revealing evidence of difficulties among the participants. When considering the learning difficulties it is important to note that the students were not necessarily capable of transferring prior conceptual knowledge from one situation to another. More specifically, using the tangible model appeared to help the students understand the facets *random molecular collisions*, *differential stability*, and *error correction* of the process. In Paper II we suggest that this could be due to the inherently abstract molecular process becoming authentic for the students when they interact with the model.

**Paper III**

The qualitative analysis of the transcripts of group discussions in Paper III suggests that the students included in the study had very limited or no prior knowledge of the process of self-assembly. The data showed that they possessed both relevant and irrelevant pre-knowledge from related domains that they tried to apply to describe and explain the self-assembly process, which resulted in both correct and incorrect reasoning. There is clear evidence in the empirical data of reasoning difficulties related to the concept that higher order structures can form spontaneously (and reversibly) as a result of random interactions between self-assembling components. Thus, the data showed that a highly ordered complex is not expected to be formed by random processes – this is indeed counter-intuitive – and the model induced a conceptual conflict. However, by discussing ideas and
8. Summary of the Results of the Papers

using the model to test hypotheses and consider possible explanations, the
students successfully accommodating a new conception, thereby reaching a
scientific explanation of the process. In particular, the tangible model had two
functions, first as an “eye-opener”, and then as a “thinking tool”, and acted as a
facilitator in the group discussions by reducing the student’s conceptual
threshold, allowing them to accept the counter-intuitive aspects and integrate
relevant elements of their prior knowledge. Moreover, the analysis of both the
group discussion and interview transcripts showed that students recalled the
scientific content by connecting the statements to the context of the group
discussion and the tangible model.

In summary, the findings presented in Paper III indicate the tangible model
and the group discussions contributed to students’ conceptual change
(accommodation of the new conception) in several ways: students became aware
of the counter-intuitive aspects of self-assembly through the tangible model;
students’ intuitive expectations were challenged and they personally felt the need
for an explanation of how the process of self-assembly occurs; students engaged
in a fruitful discussion of different hypotheses about how self-assembly proceeds;
students experienced a “conceptual conflict” that enhanced their accommodation
(conceptual change). The students’ experience of the molecular process of self-
assembly was clearly a key factor for their shift in conceptual understanding.

Paper IV

Grasping the reversibility of molecular phenomena in life science contexts
appears to be rather challenging for students. To explore the origins of such
difficulties, in Paper IV applied the CharM-framework (Characteristics of
Metaphors), designed to envision the relationships between the message intended
to be conveyed by an external representation with its influence on spoken
language, and the characteristics of different metaphors and their effects on the
formation of students’ internal mental representations (see Figure 1 in Paper IV).

The qualitative analysis of the group discussion transcripts revealed that
students in all six groups used a variety of metaphors while reasoning about ATP
synthesis, likening it for example to a mill, robot, motor and/or spring. Many of
the metaphors generated by the students were very machine-orientated. The
8. Summary of the Results of the Papers

Qualitative analysis of the transcript of the interview with the animator revealed two intended metaphors in the animation design: a machine, introduced by the animator himself, and a watermill, derived from the written text in the textbook. The data examined in Paper IV suggest that the interpreter’s prior knowledge and the design of the external representation were key factors in the process of interpretation.

The analysis of the metaphors machine and watermill showed that some of their identified characteristics were relevant and mapped well from the literal source domain to the new target domain. For example, a machine needs fuel to run and a watermill needs water to spin, while correspondingly the proton gradient over the mitochondrial membrane is required to generate the movements of ATP synthase that result in catalysis of ATP synthesis. However, six characteristics of the metaphors were also recognised (four for the machine-metaphor and two for the watermill-metaphor) that are unsatisfactory for explaining ATP synthesis and thus could cause potential problems for successful learning since they could tempt students to believe that the process is either deterministic or irreversible.

In summary, this Paper shows that metaphors come to life at the interface of external representations, molecular processes and student learning. It also shows that the CharM-framework provides an appropriate approach for understanding these complex relationships. However, although the analysed metaphors appear to be valuable for students’ meaning-making, some of the identified problematic characteristics of the machine and watermill metaphors are possible sources of students’ difficulties with understanding that ATP synthesis is a reversible and non-deterministic process. The design (choice of symbols and signs) of external representations is highly important and influences students’ intuitive thinking and use of metaphors in their meaning-making of molecular phenomenon. The language in the external representations mirrors the designer’s intentions and prior knowledge of the process.

Additional Results

Although the studies described in Papers II and III were not specifically designed to investigate students’ emotions during learning, in both studies a correlation
was detected between positive emotions of enjoyment and students’ conceptual understanding. Thus, the importance of emotions in students’ learning is one finding that has emerged from the studies. Paper II demonstrated that the TLS was associated with positive attitudes; the group discussions included many spontaneous expressions of enjoyment and the interviewees highlighted the positive benefits of peer-engagement in the group discussions and interaction with the tangible model. In addition, most of the groups participating in the studies in Paper III expressed a joyful feeling when they encountered the conceptual conflict and their accommodation of a new conception. The analysis of the interview transcripts supports this, as all five interviewed students made positive remarks about the tangible model when discussing the process. This finding is also considered and reflected upon in the Discussion.
9. Discussion

This discussion is based on the results presented in the appended papers. The research questions posed are addressed and considered both separately and from an integrated, discursive perspective. My overall focus lies in the value of representations as conceptual tools, i.e. if and (and if so how) they can support students’ conceptual understanding of molecular processes.

Core Facets of Self-assembly

In the analysis in a former manuscript (Höst et al., 2010) we performed a conceptual analysis of self-assembly, as presented in the scientific literature, to identify the core facets required for a conceptual understanding of self-assembly. Accordingly, the empirical data in Paper II was inductively analysed with respect to the five identified facets. According to the literature these five facets appeared to be most prominent, but results of the empirical study implied that students also considered a sixth facet while discussing the process. The analysis indicated that students frequently referred to structural complementarity in responses to the open-ended questions, thus this notion was added as another core facet. This can be justified by the fact that the stability of the resulting structures in biological self-assembling systems is ensured by cooperatively reinforcing intermolecular interactions between structurally complementary surfaces (Williamson, 2008). In addition, the concept is not only important for the process of self-assembly but also for diverse processes in organisms, for example the affinity of enzymes and substrates depends on the complementarity of their shapes. Thus, knowledge of structural complementarity could be seen as important for students’ learning in molecular life science generally. In summary, six facets were identified (random
9. Discussion

molecular collisions, reversibility, differential stability, influence of temperature, error-correction and structural complementarity), for definitions see Paper I, Table 1. As pointed out in Paper I, it is possible that the presented view of self-assembly could be further improved, but these six facets are clearly fundamental and supported by the scientific literature.

The Role of Representations for Students’ Conceptual Understanding

The analysis of responses to the open-ended question in the pre- and post-tests presented in Papers I and II provide indications of students’ conceptions of the facets separately and allow us to compare results obtained using the same probe in two different studies. The results in both cases show that students’ conceptual understanding of the facets random molecular collision and error-correction improved between the tests. Thus, they demonstrate that the interventions (group discussion and interaction with the tangible model or image) had positive effects on students’ conceptual understanding of these facets, which are strongly related to several reported aspects of molecular processes that are reportedly difficult for students to grasp. These include: the particulate nature of matter (Gabel & Samuel, 1987; Harrison & Treagust, 2002), the intrinsic motion of particles (Novick & Nussbaum, 1978) and diffusion (Friedler et al., 1987; Garvin-Doxas & Klymkowsky, 2008; Odom, 1995; Westbrook & Marek, 1991). The results are consistent with previous reports that discussions of an exploratory nature and hands-on practical activities are beneficial for students’ cognitive development (Webb & Treagust, 2006). Hageman (2010) also found that students who constructed models of biochemical structures on a weekly basis gave more sophisticated answers than controls and that more complex structures were constructed in small-group activities. When considering the tangible model, active hands-on manipulations seem to promote the learning of complex and abstract science concepts (Glasson, 1989; Vesilind & Jones, 1996).

One of the papers also indicated that students’ conceptual understanding of the facets reversibility and differential stability improved, but in each case not the other paper. In addition, Paper III showed that students used both relevant and
9. Discussion

irrelevant knowledge from related domains when they tried to describe and explain the process, which resulted in both correct and incorrect reasoning. Notably, in responses to the open-ended question recorded in Paper II, students expressed a view of the facet influence of temperature that conflicted with the properties of the tangible model, despite some prior conceptual knowledge from other situations of the effect of temperature on the movement of molecules. These findings together imply that students had some knowledge of various aspects related to some of the three facets, but were not necessarily capable of transferring this knowledge from one domain to another. Domain-specific knowledge is unlikely to be transferred from one situation to another if no explicit transfer-inducing instruction is given (Dochy, 1992). Hence, occasionally relevant relationships between students’ prior knowledge from related domains and the external representation (Justi & Gilbert, 2002) were created, but sometimes these relationships were absent or vague. This suggests that students’ ability to discern the relevant model features are important for their successful transfer of knowledge. Accordingly, fostering skills and knowledge that are transferable to new situations, and the ability to transfer knowledge from one situation to another, have been proposed as central educational goals (e.g. Bransford & Schwartz, 1999; Goldstone et al. 2005). Goldstone et al. (2005) also suggest that one of the most effective strategies for fostering transfer of knowledge is to encourage students to actively interpret perceptual situations. The events and/or interactions in such a situation influence students and correct their interpretations, then the interpretations give meaning to events. Furthermore, since the studies showed that the students developed a conceptual understanding of the facet error-correction, which also include the reversibility of bonding, it is surprising that they did not include reversibility in their responses to the open-ended question in Paper II.

It has also been previously shown that students in high school, college and higher education have difficulties with understanding chemical equilibrium (Thomas & Schwenz, 1998), and various alternative conceptions regarding various aspects of chemical equilibrium have been identified among students and teachers (Banerjee, 1991). Thus, there appears to be something intrinsically difficult to grasp and describe about the reversibility of molecular processes
9. Discussion

(Banerjee, 1995; Stadig Degerman & Tibell, 2012; Villafañe et al., 2011). A possible explanation for this difficulty was investigated in Paper IV. It appeared that the metaphors machine and watermill might stimulate students to think of ATP synthesis as a deterministic and irreversible process. This reflects a common problem: terms in Molecular Life Science do not have any equivalent terms in everyday language (Tibell & Rundgren, 2010), which may cause problems since it makes reasoning about abstract molecular processes difficult (Reif & Larkin, 1991). Hence, teachers use metaphors to help their students gain a deeper understanding of scientific concepts (Orgill & Bodner, 2006). However, since language is important for learning through pointing out and drawing attention to concepts (Allwood, 1983) the verbal representations (metaphors) may afford ATP synthesis certain unintended characteristics. So, even if the analysed metaphors were helpful conceptual tools for students’ learning (Duit, 1991; Treagust et al., 1996/1998), some of their identified problematic characteristics could also have contributed to the students’ difficulties. Similarly, Aubusson et al. (2006) have suggested that such representations can either mislead or lead people to better understanding. As novices are initially dependent on language for their meaning-making, and the explicit meaning of language used influences and shapes individuals’ perceived reality (Hung, 2001), it could be difficult for students to tell which characteristics of a metaphor are relevant and should be transferred to the conceptual domain to form an internal representation.

Representations are now recognized as important conceptual tools that provide students with information that cannot be readily conveyed by other means of instruction (Kozma et al., 2000; Phillips et al., 2010). Notably, in chemistry education, models assist students to develop mental representations of chemical phenomena (Chittelborough & Treagust, 2007). However, difficulties in interpreting external representations are potential obstacles to learning and could result in alternative conceptions and incorrect reasoning (Schönborn et al., 2002). In addition to the discussions above, Paper I provides information about how the two external representations, the tangible model and image, differently influenced students’ conceptual understanding of self-assembly. The analysis of responses to the open-ended questions in the post-test showed that students who had interacted with the tangible model provided more multi-faceted and
complex responses than the students who had viewed the image. However, many students who interacted with the image more often included structural complementarities involved in the virus capsid assembly process in the open-ended questions than the students in the model group. This could be an effect of the image being constructed (probably) to support structural understanding of virus assembly. In contrast, the properties of the tangible model may support students’ understanding of self-assembly in terms of the facets related to movement.

Representations represent the world by using similarities between them and the aspect of the world they are representing (Giere, 2004), and the presence or lack of corresponding point-by-points between the two (Black, 1962) will affect what is observable in the representations. Thus, the differences in responses of students who had interacted with the two representations used in Paper I could reflect differences in how the external representations convey relevant aspects of the learning content. This hypothesis is supported by the fact that the tangible model incorporates a wider set of features that are analogous to the properties of the molecular system it is designed to represent, and the consistency of the results (both quantitative and qualitative) obtained in Papers I and II regarding students’ improvement of their conceptual understanding of the facet random molecular collisions. Thus, the tangible model appears to be a powerful tool for supporting students’ conceptual understanding of the dynamic aspects of self-assembly. In Paper II we explicitly argue that interaction with the tangible model may decrease the risk of students developing ideas about a guiding principle in self-assembly. The tangible model also appears to help students to envision the visual-spatial relations involved (Uttal & O’Doherty, 2008), which facilitate attempts to perceive all structures and their relations. Similarly, Pillay (1998) found that tangible models were most helpful for students in an assembly task, since students only needed to interpret the information provided and did not have any problems associated with hidden structures. The benefit of using tangible models in education is further supported by several other studies (Dori & Barak, 2001; Hageman, 2010; Harris et al., 2009; Montessori, 1912; Roberts et al., 2005; Rotbain et al., 2006). Roberts et al. (2005) found that students perceived tangible models to be the most helpful tools for learning about protein structure.
9. Discussion

and function. Harris et al. (2009) concluded that students preferentially used tactile models when challenged with questions that required higher-level thinking. Rotbain et al. (2006) found that students who were given a tangible (physical) model gave more correct and profound answers than students who were given illustrations.

Moreover, metaphors derive from experience; in an educational context this implies that prior knowledge of the real-life domain, as well as of the scientific domain, provides foundations for students’ use of metaphorical language. Correspondingly, the analysis in Paper IV showed that metaphors students generated in the discussion were very machine-like, reminiscent of objects and processes that the students had presumably experienced in everyday life. The analysis of the interview with the animator showed that he introduced the machine-metaphor deliberately, and designed the animation according to his intentions and prior knowledge. Thus, the metaphors students expressed were strongly influence by the design of the animation, in line with the CharM-framework.

In summary, the discussion suggests that students’ ability to discern the relevant model features are important for their successful transfer of knowledge from related concepts or situations. Moreover, both Papers I and IV showed that the design of the external representations (image, tangible model and animation) influenced students’ conceptual understanding and metaphorical language. Thus, the design (choice of symbols and signs) of external representations is highly important and is one factor that influences students’ conceptual understanding and language in their meaning-making of molecular processes. The metaphors, in turn, provide students with both relevant and problematic characteristics that they have to differentiate between. Thus, when faced with external representations students are often required to manage two somewhat difficult processes (interpreting the representation and the metaphors used), which may create challenges for their learning.

Counter-intuitive Aspects of Self-assembly

Several authors acknowledge the importance of considering what students already know for the learning process (e.g. Ausubel, 1968; Chittleborough & Treagust,
9. Discussion

2007; Glaser, 1983). The theoretical frame of constructivism and social constructivism also supports the view that knowledge acquisition is dependent on individuals’ prior knowledge and beliefs (Hung, 2001). The analyses in Papers I, II, and III indicate that students were unfamiliar with the molecular processes of self-assembly prior to the studies. They were unable to identify the relevant facets needed for explaining the process and their pre-test responses indicated no prior conceptions of the process of self-assembly. Since we had already found that the process is rarely addressed in biochemistry textbooks this discovery was not surprising. The students interviewed in Papers II stated that they had not thought about the process prior to the TLS and it was a process they took for granted. Since intuitive thoughts come initially fast and spontaneously to mind without conscious act or effort (Kahneman & Frederick, 2002) it is highly probable that student intuitive ideas are instantly triggered when confronted with this “new” non-perceptual bio-molecular process. diSessa (2000) put forward that students use their intuitive knowledge of the worlds to build an scientific understanding. In Paper III we find evidence in our data for reasoning difficulties in relation to the fact that higher order structures form spontaneously (and reversibly) as a result of random interactions between the constituent self-assembling components, and that students find this aspects of self-assembly counter-intuitive.

Hung (2001) suggests that humans in a given discourse develop similar expectations of certain phenomena based on the similar use of language to approach the world in order to reach understanding and socializing, thereby facilitating both understanding (or misunderstanding). The results from the group discussions in Paper III manifested an induced conflict in all groups, hence the focal process must entail counter-intuitive aspects. As knowledge is constructed socially and then assimilated by individuals, one could say that the students experienced the process of self-assembly as counter-intuitive. Furthermore, although there was a striking improvement, in terms of learning gains, regarding the facet of random molecular collisions in Paper II some of the students tried to apply generic “drivers”, for example enzymes, to explain the process. This finding also supports the hypothesis that some aspects of the self-assembly process are experienced as counter-intuitive, although it probably
reflects both students’ attempts to explain the counter-intuitive aspects of the process and incorrect application of their prior knowledge that enzymes catalyse almost every reaction in cells.

The reasoning in Paper III is based on several findings connected to humans’ tendencies to explain randomness as opposite to order (Resnick, 1996), for instance that: humans’ tendency to attribute order in a system to an agent and to think that inanimate objects create disorder rather than order (Friedman, 2001; Resnick, 1996), the tendency to explain phenomena by some kind of central control or deterministic causality (Resnick, 1996; Resnick & Wilensky, 1993; Wilensky & Resnick, 1999), and resistance to build upon ideas of stochastic and decentralized processes (Feltovich, Spiro, & Coulson, 1989; Resnick, 1994/1996; Wilensky & Resnick, 1999). These tendencies of humans are not necessarily only related to students’ learning of self-assembly but could also be a source of the many learning difficulties found in the science education literature related to students’ difficulties with understanding aspects of the random and reversible nature of phenomena generally (Banerjee, 1995; Friedler et al, 1987; Gabel & Samuel, 1987; Garvin-Doxas & Klymkowsky, 2008; Harrisson & Tregust, 2002; McCluskey, 1983; Novick & Nussbaum, 1981; Odom & Barrow, 1995; Villafañe et al., 2011; Westbrook & Marek, 1991), such as equilibrium or diffusion. In addition, several authors have proposed that one source of students’ difficulties in science learning could be the everyday experiences students bring into the learning situation (Cousin, 2006; Nussbaum & Novick, 1982; Pedersen & Halldén, 1994; Perkins, 1999). Furthermore, according to the fine-grained constructivist view (Smith et al., 1994; Tirosh et al., 1998): conceptual change is the modification of one’s intuitive generalizations to more coherent and united structures (Elby, 2000); intuitive knowledge is attained from generalisations of experiences that are loosely connected to other elements of knowledge; and its activation is context-dependent (Hammer & Elby, 2002; Smith et al., 1994; Tirosh et al, 1998). Therefore it is important to further discuss ways to facilitate students’ successful accommodation of the counter-intuitive aspects of self-assembly identified in Paper III.
Facilitating Students’ Conceptual Change of Self-assembly

Counter-intuitive concepts naturally expose students’ prior conceptions and induce a conceptual conflict and can be used for expected accommodation (Berlyne, 1965; Eylon & Linn, 1988; Gordon, 1991; Hewson & Hewson, 1984; Lesser, 1998). However, in molecular life science external representation is required to highlight the counter-intuitive aspects of a molecular process in order to show students some “observed phenomenon”. In the qualitative analysis of the group discussion and the interviews in Paper III we observed that 5 (of 6) groups experienced a conceptual change (to believing that a biological structure, such as the virus capsid, can be formed from random motion of components) by interacting with the tangible model in discussion with peers. To elucidate what helped students to change their conceptual understanding in the course of the group discussion the circumstances that may have facilitated their conceptual change should be considered. Guzzetti (2000) state that it is not enough to generate a conceptual conflict, meaning that even if some students become aware of their incorrect prior ideas they are not always able to change their conceptions. Instead, sometimes students also need to participate in discussions where they can express and discuss their ideas (Alvermann, Hynd & Qian, 1995).

The results from Papers I, II, and III all suggest that the collaborative learning environment seemed to provide a beneficial context for the students to engage in a fruitful discussion of different hypotheses about the self-assembly process. Accordingly, previous studies suggest that when students interpret counter-intuitive aspects of a phenomenon in an active and exploratory way they are confronted with the character of the phenomenon (Perkins, 1999), thus making them aware of their preconceptions (phase one in Nussbaum & Novick’s strategy). This is further supported by Jacobson & Wilensky (2006), who argue that pedagogical approaches should focus on the conceptual aspects of students’ learning as well as their intuitive beliefs and intuitions about the world.

Some or all students who participated in Studies 1 and 2 also interacted with the tangible model representing the process of self-assembly. In contrast to other tangible models used for representing this process, or aspects of it (e.g. Campbell et al., 2001; Campbell et al, 2002; Dungey, 2000; Jones et al., 2006), results obtained in these studies indicated that the tangible model could be a
9. Discussion

powerful tool for supporting students’ construction of knowledge about the
dynamic aspects of the process (see earlier discussion). Upal et al. (2007) and
Franks (2003) note that the ideal way that concepts should be presented depend,
amongst other factors, on humans’ common-sense (intuitive) notions about the
domain. As the students’ intuitive expectations did not tally with the counter-
intuitive aspects of self-assembly, their rational thinking and reasoning were
activated (Kahneman, 2003; Kahneman & Frederick, 2002). In this sense the
group discussion also presumably played an important role in the students’
conceptual understanding of the counter-intuitive aspects of the process, because
through reasoning language acts as a collective stabiliser for conceptualisations
(Allwood, 1983). However, according to Kahneman (2012), our reasoning needs
cues or explanations in order to correct such errors. Similarly, Hewson (1992)
describe how students must be provided with a credible reason for being
unsatisfied with an old conception to initiate conceptual change (Hewson 1992).
In accordance with Paper IV, this implies that the tangible model functioned as an “eye-opener” and “thinking-tool”, and convinced students that their intuition
provided them with incorrect information.

According to distributed cognition theory (Hutchins 1994), individuals’
cognitive processes, objects and the limitations of the environment mutually
affect each other (Lehtinen, 2003) and in social constructivism any learning that
takes place is a result of interactions (Hung, 2001). Thus, it can be concluded
from the presented results, with support from the theoretical framework, that
individuals’ cognitive processes and the collaborative learning environment
(including interactions with external representations and peers) are important for
students’ cognition and knowledge acquisition. The group discussion and the
tangible model jointly contributed to students’ conceptual change by making
them aware of the counter-intuitive aspects of self-assembly, and allowing them
to engage in a fruitful discussion about different hypotheses regarding the self-
assembly process and to experience a conceptual conflict that enhanced their
accommodation.

In addition, in molecular life science no direct experience of molecular
processes is possible, thus representations must both draw students’ attention to
certain features of a molecular process (Phillips et al., 2010) and provide them
9. Discussion

with an experience of the process. According to Dewey (1938) learning is a social and interactive process, thus students should develop best in an environment that focuses on fruitful experiences and interaction, organized in a manner that guides students’ learning. Thus, the tangible model made the counter-intuitive aspects of self-assembly visible to the students, gave them an experience of the process, and enabled the generation of a conceptual conflict, which was a key factor in their conceptual change and accommodation of the new conception.

The Role of Emotions in Students’ Learning

The studies presented in the appended papers were not originally designed to investigate the emotional dimension of students’ learning. However, indications of its importance were an exciting outcome of Papers II and III. This is of particular interest since ‘classical’ conceptual change research, following the pure cognitive and individual view (Posner et al., 1982), has faced challenges to develop successful instructional designs for facilitating learners’ conceptual change. Therefore, consideration of affective and contextual factors has been called for (Duit & Treagust, 2012; Pintrich et al., 1993; Zembylas, 2005). Indeed, Plato (ca. 428-347 BC) is widely quoted as having stated that “All learning has an emotional basis”, and the significance of emotions in science learning has long been highlighted (Alsop & Watts, 2002; Jidesjö, 2012; Mahn & John-Steiner, 2008; Reiss, 2005; Vygotsky, 1978). In addition, Dole & Sinatra (1998) have reviewed the literature related to conceptual change in psychology, science education and social sciences, and suggested a model for cognitive reconstruction of knowledge that includes existing conceptions, motivation, plausibility and students’ level of meta-cognitive engagement.

In accordance with the literature cited above, the transcripts of the group discussions in Papers II and III contained many spontaneous expressions of enjoyment in connection to the discussion with peers and the interaction with the tangible model, such as laughter and happy outcries. This is further supported by the interviews in Paper II, in which all five students highlighted the fun and benefits of peer-engagement in the group discussion and interacting with the tangible model. Guzzetti (2000) advocates that conceptual conflicts are inherently interesting since they question intuitive ideas. According to Deci &
Ryan (1985) and Ryan & Deci (2000) enjoyment is linked to intrinsic motivation, i.e. being “moved to act for the fun or challenge entailed rather than because of external prods, pressures, or rewards” (Ryan & Deci, 2000, p. 56). According to this line of reasoning students were intrinsically motivated during the group discussion. Pink (2010) holds that mastery is one, of three, distinguishers of intrinsic motivation. Also, Pintrich et al. (1993) and Pintrich (1999) withhold the importance considering factors such as mastery for students’ successful conceptual change. Since most of the students changed their intuitive ideas to scientifically “correct” conceptions of the counter-intuitive aspects of self-assembly they did in fact master the conflict. Thus, their mastery of the conflict may have positively influenced their intrinsic motivation. This highlights the desirability of creating a conflict that provides students with an appropriate challenge that may be possible for them to master. However, if the conflict is too challenging to solve it will probably impede learning, since students are likely to give up and lose interest in the task. D’Mello & Graesser (2012) also noted that students may become confused when they experience cognitive equilibrium (facing new unexpected knowledge), and if they do not come to accept this new knowledge it could lead to disengagement and boredom. Scott, Asoko, & Driver (1991) also note that any conflict-based strategy for enabling conceptual change is dependent on students’ willingness and ability to recognise and solve a conflict. A presented conflict, as the counter-intuitive aspects of self-assembly brought forth by the tangible model, are used as a motivational factor for searching for a better explanation (Clement, 1987; Nussbaum & Novick, 1982; Scott et al., 1991). This suggests that when encountering a task that raises a conceptual conflict it is essential to ensure that the students are assisted in their meaning-making of the scientific content in order to master the conflict.

A connection between students’ conceptual change and intrinsic motivation was found in Paper III, in which most of the groups expressed a joyful feeling concurrently with accommodation of a new conception (as they realised and accepted that the random motion of components could give rise to a virus capsid). This connection is further supported by suggestions by Pintrich (1999) that factors such as self-efficacy and confidence, autonomy, mastery and personal relevance are mediators of the process of conceptual change. Pintrich &
Schrauben (1992) also propose that motivational and emotional factors may either facilitate or constrain students’ conceptual change. The fact that students enjoyed the intervention and all associated aspects of the study design could, of course, have contributed to our positive results, but if so this reinforces the hypothesis that emotions are important elements of students’ successful conceptual change. However, Schönborn et al. (2012) also found that students were emotionally charged when encountering a conflict while using thermoimaging in conceptualising heat transfer.

In particular, the group discussion and the tangible model functioned as intrinsic motivators (Ryan & Deci, 2000) since they assisted the students to master the conflicts, which in turn helped their accommodation. Clement (1987) suggests that classroom discussions, if skilfully led, can be vehicles for internal motivation and conceptual restructuring (change). Seeking intrinsic motivation within students is particular interesting for educators since it can be a “natural wellspring” of learning (Ryan & Deci, 2000).

Conclusions

From the literature review and empirical data we found that the molecular process of self-assembly incorporates six core facets that are important for a conceptual understanding of the process. The empirical data showed that students had no prior conceptions of self-assembly and possessed little or no prior knowledge of any of the facets from related domains prior to the studies, although some students who participated in Paper III applied some knowledge (relevant and irrelevant) from other related domains, which resulted in both correct and incorrect reasoning. These findings indicate that students are not necessarily capable of transferring knowledge from related domains (situations). Students’ ability to discern relevant features of external representations is also relevant for their ability to transfer knowledge. Moreover, analysis of the results revealed that students’ answers, and conceptual understanding, depend on how an external representation conveys the relevant aspects of the learning content (its design). The tangible model proved to be a powerful tool for supporting students’ conceptual understanding of the dynamic aspects of self-assembly. It was also shown that the design of external representations influenced students’
9. Discussion

conceptual understanding and use of metaphors, which in turn provided them with both relevant and problematic characteristics that they had to differentiate between. Thus, in this case students were required to manage two somewhat difficult interpretation processes (interpreting the external representations and metaphors used), which may create challenges for their learning.

Furthermore, the process of self-assembly was shown to incorporate counter-intuitive aspects, and both the group discussion and the tangible model proved to be important facilitators’ of students’ change in conceptual understanding of the process (from existing intuitive ideas to a scientific conception of self-assembly) This was because they: enabled them to become aware of the counter-intuitive aspects of self-assembly; feel the need for an explanation of how the process occurs; engage in a fruitful discussion about different hypotheses regarding the process; and experience a “conceptual conflict” which enhanced their accommodation (conceptual change). Since we were dealing with an imperceptible molecular process the tangible model was a key factor for students’ experience of the process and their conceptual change. Lastly, providing students with a conflict-based task, problem or representation is not enough, they also have to be willing (emotionally motivated) to solve the conflict. If students are provided with appropriate means for mastering the conflict they will be intrinsically motivated. Hence, the tangible model and the group discussion functioned as intrinsic motivators.
10. Implications and Future Directions

Implications

The results from the studies presented in this thesis will hopefully contribute with valuable insights for both researchers in the field of science education and teachers facing pedagogical challenges. The molecular process of self-assembly is a general process in molecular life science and understanding it is essential for grasping how complex structures in living cells are formed. The process has also been proposed as one of the “big ideas” that are important for molecular life science students to grasp (Howitt et al., 2008; Sears, 2008). Hence, it is important for students to acquire scientific knowledge of this molecular process.

The students’ conceptual understanding of the facets identified as important in this thesis may provide a starting point for further research on students’ understanding of self-assembly. The results may also facilitate research on students’ learning of similar and related scientific concepts that incorporate one or several of the identified facets. Both self-assembly and ATP synthesis incorporate several central concepts that have been proven difficult for students to learn, for example the particulate nature of matter (e.g. Harrison & Treagust, 2002), intrinsic motion of particles (Novick & Nussbaum, 1978) and reversibility (Banerjee, 1995; Villafañe et al., 2011). In turn, understanding the particulate nature of matter is important for understanding scientific concepts such as properties of substances, phase changes, chemical reactions and equilibrium (Nakhleh, 1992; Nakhleh, et al., 2005; Novick & Naussbaum, 1978; Stavy, 1991). Moreover, Meyer & Land (2003) propose the existence of threshold concepts within disciplines. When internalizing threshold concepts we move from one state of knowing to another (Kabo & Baillie, 2009), and
10. Implications and Future Directions

transform our way of thinking about a discipline (Meyer & Land, 2003). Thus, grasping threshold concepts is crucial for students' learning and progress within a discipline. Randomness, thinking at sub-microscopic and subcellular levels, scale (temporal and spatial), probability and dynamics are all proposed to be threshold concepts (Ross et al., 2010). Thus, understanding the concepts of self-assembly and ATP synthesis are also important for students' progression and learning in this domain. Theoretical considerations presented in Paper III, also indicate that not only the randomness of self-assembly, but also the notion that this kind of behaviour between components can give rise to a biological complex adds complexity to the concept of randomness. Accordingly, Garvin-Doxas & Klymkowsky (2008) observed that in some cases students may understand the randomness of diffusion but be unable to make the connection with emergent behaviour in systems and well-defined/directed biological processes (Kottonau, 2011). This notion should possibly be added to the threshold concepts in molecular life science. Knowledge of the six identified facets of the process may assist students in their continued learning in molecular life science and science in general.

Representations are essential conceptual tools for scientific activities (Coll et al., 2005; Kozma et al., 2000). The studies underlying this thesis have shown that external representations and metaphorical language can facilitate students’ meaning-making with respect to imperceptible entities. However, they have also shown that representations and metaphorical language may cause problems for students’ learning, depending on how they interpret the representations. In addition, metaphors used in biochemistry textbooks are rarely presented in a satisfactory way, seldom explained and elucidated to students (Orgill & Bodner, 2006), and the same is probably true for metaphors and analogies used in the classroom. This is especially worrying since metaphors implicitly influence the way we think and act (Lakoff & Johnson, 1980). Awareness of the characteristics of the metaphors machine and watermill will hopefully alert teachers to ways in which metaphors may influence students’ conceptualisation of the scientific concepts they are supposed to describe, when applied to ATP synthase.

It is important to note that language must be optional and incomplete in order to adapt to new situations, and sometimes linguistic expressions remain
rather vague if this suits the given communication (Allwood, 1983). Thus, learners can use language as a facilitator for learning new conceptions and use partly verbalised elements in their thinking. It may be important for metaphors to remain vague in order to coordinate and promote creativity, even if this may create challenges for novice learners and place responsibility on teachers. Allwood (1983) also states that novices are initially dependent on language, and perhaps its explicit meaning, but as their knowledge develops this dependence decreases. Taken together, our results and previous findings indicate that students’ ability to transfer knowledge from related domains and their conceptual understanding are highly influenced by their interpretations of the design of external representations and characteristics of the metaphors used. The challenge for educators lies in choosing representations that convey the aspects of the learning content that they are intend to teach and assist students in their meaning-making of the representations by remaining informed of students’ background knowledge and interpretations. As Phillips et al. (2010) note, the success of any external representation to teach and communicate lies in the eyes and brain of the creator and students. Hence, the background knowledge and interpretation abilities of students strongly influence the efficacy of any external representation.

The findings about the aspects of self-assembly that students experienced as counter-intuitive demonstrate the importance of considering students’ expectations and prior knowledge when learning science. This is because many molecular life science phenomena and processes deviate from the behaviour of macro level events and processes. Phenomena, such as molecular processes, that are not dependent on or attributed to humans’ patterns of action place great demands on learners (Wilensky, 1991). Counter-intuitive aspects of molecular processes could also be sources of the many learning difficulties associated with the random and reversible nature of phenomena described in the science education literature. When teaching these concepts teachers need to provide students with cues and explanations for the new, unexpected knowledge (Kahneman, 2012). The results presented in this thesis show that allowing students to discuss and reason about the process of self-assembly while they interacted with the tangible model facilitated their accommodation of the counter-intuitive aspects of the process. As stated in the Introduction, in
10. Implications and Future Directions

molecular life science the purpose of representations is not only to draw attention to certain features (Phillips et al., 2010), but also to provide students with an illuminating experience of the represented phenomena. Providing students with experience of phenomena associated with molecular concepts that incorporate counter-intuitive aspects (facets that students’ intuitions cannot explain) through representations is a key factor for their understanding of the concepts, since direct experience of them is impossible. Considering the external representations used in the studies this thesis is based upon, the tangible model could be a possible entry point for discussions about the random aspects of molecular processes in general.

The results also indicate, in accordance with Nussbaum & Novick (1978), that conceptual conflicts may be fruitful for teaching and learning since they stimulate students’ interest and can enhance students’ accommodation. However, it is not enough to provide students with a conflict-based challenge for successful conceptual change; they also need to be emotionally motivated, and if they are provided with appropriate means for mastering a conflict they will be intrinsically motivated. Zembylas (2005) discusses whether the term “conceptual change” is appropriate, since not only changing concepts, but also students’ epistemological and motivational beliefs, metacognitive abilities and emotional changes are important for changing their knowledge frame. Results presented in this thesis support this view. The importance of considering the emotional dimension for conceptual change is also advocated in the science education literature (Duit & Treagust, 2003/2012, Pintrich, Marx, & Boyle, 1993; Zembylas, 2005). Students’ emotions are fruitfully used to engage their interest in other school subjects, for example social sciences (e.g. Sadler & Zeidler, 2004/2005), and it seems that emotions may also play an important role in learning concepts and processes in molecular life science.

Considering my theoretical framework, incorporating elements of distributed cognition, constructivism and social constructivism, one could also wonder, in accordance with Zembylas (2005), if we should also consider conceptual change to be a collective process rather than a product of solely individual processes. According to this collective view, individuals interact and construct emotions, beliefs and conceptions together. Results presented in thesis
show that it could be advantageous to interpret learning in a broader sense (Illeris, 2003). Thus, as previously advocated (Vygotsky, 1978; Zembylas, 2005), further research should perhaps focus on the link between emotions and cognition, which social constructivism (for example) has been criticized for ignoring (Nelmes, 2003; Op’t Eynde, De Corte & Verschaffel, 2006; Zembylas, 2005).

The theoretical framework was useful for guiding our methodological choices and both interpreting and understanding the empirical data collected in the studies. Both social constructivism (e.g. Hung, 2001) and distributed cognition (Hutchins, 1994; Hollan et al., 2000) stress the importance of interactions between people and their interaction with the environment for individuals’ knowledge acquisition and the cognitive system, respectively. Key elements of an educational environment normally include a teacher, and Studies I-IV showed that the individual learner, his/her peers, and socio-culturally formed conceptual tools (Lehtinen et al., 1999; Salomon, 1993) can all make important contributions to students’ conceptual understanding of self-assembly and ATP synthesis. As previously observed, cultural factors, the social context and emotions are all important for our cognitive development (Vygotsky, 1978), and learning takes place as the result of interactions both among peers and with representations (Hung, 2001). The results presented and discussed in this thesis will hopefully help teachers in life sciences to facilitate students’ learning of these important concepts.

Future Research

Finally, we must look forward and discuss some possible interesting research avenues indicated by the results presented in this thesis. Most of the groups expressed a joyful feeling during their interaction with peers and the tangible model, and as they accommodated a new conception. The interviewed students also mentioned such feelings. The implication that learning is associated with human motivation was an unanticipated finding of the studies, which were not designed to explore the link. Thus, it would be exciting to design a study to focus on the emotional dimension during learning in more detail, particularly in the course of students’ conceptual change. Motivation is believed to give rise to
10. Implications and Future Directions

action (Ryan & Deci, 2000), and as we act with each other and our environment we create meaning (Prawat & Floden, 1994). More in-depth research on the interactive learning process between students, and between students and representations in group discussions, could therefore be very fruitful, possibly using video recordings rather than audio recordings to obtain more detailed information.

Animations, which are used for showing dynamic changes in molecular processes, have been shown to sometimes be overwhelming and overload students’ cognitive resources (Lowe, 2003; Tversky, Bauer Morrison & Betancourt, 2002). This could be used as a basis to investigate the benefits of tangible models and the interaction between students and models. In a study performed by Alač (2005) a researcher integrated dynamic aspects of phenomena presented in static representations with body movements (for example gestures). This was a consequence of that the static representation did not show any of the dynamic properties that the researcher wanted to illustrate. The tangible model used in Papers I-III naturally integrates such activity since students need to hold and shake the model for it to show the process of self-assembly. Dahlbäck et al. (2012) suggest that the actions the researcher performed in Alač’s study were themselves manifestations of thought processes. As the distributed cognition perspective seems to be incorporating embodied aspects of cognition it would be interesting to investigate the role of the tangible model, and perhaps gestures, in students’ conceptualisation of the self-assembly process in greater depth. In addition, the numerous studies cited in the discussion that advocate the benefits of using tangible models (e.g. Gabel & Sherwood, 1980; Hageman, 2010; Harris et al., 2009; Montessori, 1912; Roberts et al., 2005; Rotbain et al., 2006), hand-on practical activities (Webb & Treagust, 2006), and active manipulation (Glasson, 1989; Vesilind & Jones, 1996) support the potential value of the proposed study. Using intervention groups and controls, and interaction with the model as the only modulated variable, may be appropriate.
11. References


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11. References


11. References


11. References

papers presented at the 8th Conference of European Researchers in Didactics of Biology (ERIDOB), Braga, Portugal. (pp. 67-77). Braga, Portugal: CIEC, Universidade do Minho.


11. References


11. References


11. References


Pintrich, P. R., Marx, R., & Boyle, R. (1993). Beyond cold conceptual change: the role of motivational beliefs and classroom contextual factors in the
11. References


11. References


11. References


11. References

Department of Science and Technology, Linköping University. ISBN: 978-91-7519-954-2


11. References


11. References


Appendix 1: Interview Guide (Studies 1 and 2)

Preparation
1. Welcome
2. Permission to make audio recordings - Informed consent form

Recording starts
1. Date
2. Name
3. Use of visualizations
   a. Do you usually look at the text, the picture, or both text and picture first when learn about something?
   b. Do you usually use pictures, models etc.? If so, how?
   c. Do you find it hard or easy to understand pictures, models, animations etc?
4. Self-assembly tutorial
   a. How did you experience the group discussion? Did you learn anything new during the discussion?
5. The concept of self-assembly
   a. Did you know anything about self-assembly before this tutorial?
   b. Did you learn anything new? What? When?
   c. Is it something in particular that you find hard/difficult to understand regarding self-assembly?
   d. Use virus capsid assembly as an example and ask the student to explain the following facets:
12. Appendix

Random molecular collisions
Reversibility
Influence of temperature
Differential stability
Error correction

6. Please, comment your answer on statement 8 in the questionnaire.
7. Individual questions

Finishing
1. Turn of recording equipment
2. Thank you!
3. Questions?

Appendix 2: Interview Guide (Study 3)

Introduction
1. In short, what is your educational and professional background? (Relevant background for the purpose of the interview)
2. It is our understanding correct that the animation is dated 2002 and was produced for “The Molecular Biology of the Cell” by Alberts et al.?
3. Please describe how you obtained the commission to produce the ATP-animation? Please explain to what extend the editors of “The molecular biology of the Cell” were involved, why you were chosen and when it occurred.
4. It is our interpretation that you produced the subtitles to the animation and Yoshida produced the video component (i.e. part 4), is this correct?
5. Were there any other people involved in the production of the animation?

Background
1. How was the commission formulated/described?
2. How specified and detailed was the job/task? What were the specifications? (e.g. scientific content requirements, color scale, consideration of learning aims, timeframe, etc.)
12. Appendix

3. What overall aim and limits did you receive with the instructions for producing the animation?
4. To what extent were you required to have the design of the animation, such as its symbolic composition and graphical features, aligned with “conventions” in the molecular biology and biochemistry field? If so, was there any such guidance for doing so? If so, was this difficult to achieve? Were there any obstacles?
5. Did you collaborate with Paul Boyer (or John Walker or Jens Skou) during design, and/or how did you connect your design to the scientific knowledge of the mechanism of ATP-synthase?
6. What strategy did you use while composing the animation – e.g. iteratively with feedback from someone or in a more sequential manner?
7. Concerning the narration – did you get it before, after or in parallel with your work of composing the animation?
8. Did you feel that your work was under certain constraints or could you work as you usually do?
9. Do you still find this way of working appealing?

Intentions
1. What were your intentions with the design of the animation?
2. Please could you describe the scientific knowledge that you wanted to convey in the different parts of the animation?
3. How close did you intend to follow the current scientific knowledge of the time?
4. Please elucidate your general [step-wise] reasoning process(es) that culminated in the final animation that you produced.
5. What were your intentions?

Semiotics in the animation
1. Could you comment on the relationship between the representation of time and scale in the animation? (E.g. real time, proton flow, ATP-synthesis and rotor speed, scale, proteins, membrane, protons, ATP/ADP/P molecules)
2. Could you please comment on the following:
12. Appendix

• your choice of colors;
• your choice of symbolism? (Part I: Protein subunits based on structure, while membrane symbolism, Protons as boxed and ATP/ADP/P as tickets/dollar bills);
• your choice to show no protons on the inside of the membrane in A1;
• your choice to show no phospholipids constituting the membrane in A2.

3. Please comment on what you intended to show with the “flash”? (In A2: Protein structure symbolism, no membrane, still protons as boxes and ATP/ADP/P as tickets/dollar bills)

The illustrator’s reflections on students’ interpretation

1. Provide your reflections on the intention of your design with respect to the following examples of students’ interpretations and comments obtained during the study described above (please feel free in your thinking and expose any reflections that come to mind).

Reflections and lesson learned

1. Given your responses to the questions above, are there any specific changes to the design of the animation that you would incorporate (assuming that you could design it from scratch)? Please take your time and feel free to express absolutely anything that comes to mind.

2. Based on your professional design experience, please could you expand upon how you think these specific changes in the design would improve students’ interpretation of the animation?

3. To what extent do you think that you integrated your own metaphorical and analogical ideas into the design of the animation?

Appendix 3: Discussion Guideline (Studies 1 and 2)

Consider the model of a virus capsid in the container. It consists of twelve subunits. In reality, each of the subunits is composed of five identical proteins. Thus, the complete capsid consists of 60 protein molecules.
Task 1
Remove the subunits from the container and try to assemble the subunits into a complete virus capsid by hand.

*How do you think such virus capsids assemble in reality?*

Task 2
Break the capsid and place the subunits in the container, and then close the container. Now try to assemble the subunits into a complete virus capsid.

*Does each subunit always end up in the same place in the capsid?*
*Do the subunits attach to the growing capsid in the same order each time it assembles?*
*What makes it possible for a subunit to bind to another subunit?*
*Do you think that the assembly process is random or guided? Why?*

Task 3
Try to simulate an increased temperature in the container. Then try again to assemble the subunits into a complete capsid under the high-temperature condition. Try to simulate a decreased temperature in the container. Then try again to assemble the subunits into a complete capsid under the low-temperature condition.

*How is the process of self-assembly influenced by temperature?*
*Why does the process progress differently at the different temperatures?*

Task 4
The formation of each bond between the subunits is reversible. Next time you assemble the subunits into a capsid, take extra notice of any cases where a subunit detaches from another subunit or a complex of subunits.

*Why do subunits detach from each other?*

Task 5
Open the container and pick up the subunits. Examine the stability of a complex consisting of two subunits. Then add one more subunit and examine the stability
of the three-piece complex. Finally, assemble the complete capsid and examine the stability.

Can you feel any differences in the stability between the different complexes?
How is the capsid stability influenced by temperature?
What factors determine the thermodynamic stability?

Task 6
Two subunits might attach to each other in the wrong way. Put the subunits back into the container. The next time you assemble the capsid, make pauses to observe the different complexes between subunits. Take extra notice of any wrongly formed complexes.

What happens to the wrongly formed complexes during assembly?
How does the error correction mechanism work?

Task 7
It is important to also consider the limitations of a model. Although a model might clarify and explain certain aspects of a phenomenon, no model is a perfect reflection of reality. In relation to the tangible model used here, consider the following questions:

What other environmental factors, besides temperature, can influence the process of self-assembly in virus-production in a cell?
What limitations or simplifications can you see in the tangible model?
What is the significance of the container dimensions?

Appendix 4: Discussion Guideline (Study 3)
Discuss and answer the following questions together as a group. Hand in one sheet for each group.

1. What is the central message in the animation “ATPas_del01.mov”?
2. What is the main difference between ”ATPas_del01.mov” and ”ATPas_del02.mov”?

12. Appendix
3. What is the driving force for ATP synthesis? How is this energy transformation achieved?
4. What happens if the concentration of protons is larger on the inside of the mitochondrial membrane than on the outside?


