Elisabeth Netzell

Using models and representations in learning and teaching about the atom
A systematic literature review

Examensarbete inom Fysik, forskningskonsumtion, grundläggande nivå, 15 hp 93XFY1

LIU-GY-L-G--15/118—SE

Institutionen för fysik, kemi och biologi
HT 2014
Title: Using models and representations in learning and teaching about the atom - A systematic literature review

Författare: Elisabeth Netzell

Sammanfattning

This study is a systematic literature review on the role of models and representations in the teaching, learning and understanding of the atom and atomic concepts. The aim of the study is to investigate the role of different visual representations, what models and representations are used in the science classroom, how learners interpret different external representations of the atom, what mental models students construct, and how the representations can be used and designed for meaningful learning and teaching of the atom and atomic concepts.

In this systematic literature review, a combination of different databases was used to search for literature, namely ERIC, Scopus and Google Scholar. Some limiters were used to narrow down the returned results: the articles should be peer-reviewed and be published 1990-01-01 or later. Ten of the returned articles were included for individual analysis in the study.

The results of the study show that students often find concepts of atomic structure difficult and confusing. The abstract microscopic world of atoms cannot be seen with the naked eye, and models are therefore necessary and crucial educational tools for teaching atomic concepts in school. However, when using a model, it is important for the teacher to explain the rules of the model, and the advantages and limitations of the representation must be discussed. Analysis of the included articles revealed three types of representations used to represent atomic phenomena: two-dimensional static diagrams or pictures (e.g. a picture of the atom), three-dimensional videos or simulations (e.g. virtual reality simulations), and visual analogies (e.g. the Bohr planetary model of the atom). The use of simulations and interactive learning environments seem to have a positive effect on students’ learning. One of the studies, described in the articles included for analysis, showed that students appreciated the use of virtual reality simulations, since it made abstract concepts easier to understand when they could be visualized.

Nyckelord

Physics education, chemistry education, models, representations, atom, atomic concepts, mental models, alternative conceptions, teaching, student understanding
# Table of contents

1 Introduction .................................................................................................................. 1

2 Aim of the study .......................................................................................................... 2

3 Background ................................................................................................................ 3

3.1 Definitions ................................................................................................................ 3

3.2 Theoretical framework ........................................................................................... 4

3.2.1 Role of models in science education ................................................................. 5

3.2.2 Difficulties when interpreting and using models .............................................. 6

3.2.3 What are the purposes, uses and functions of multiple representations in communication of scientific concepts? ................................................................. 7

3.2.4 How do learners interpret and understand different representations? ........... 9

3.2.5 How are multiple representations designed to support effective learning? ....... 10

3.2.5.1 Translating between more than one representation ...................................... 11

3.2.5.2 Constructivism and learning science ............................................................. 12

3.2.6 Models to describe and represent the atom ...................................................... 13

3.2.6.1 Historic models to describe the atom ............................................................. 13

3.2.6.2 Students’ conceptions of the atom ................................................................. 15

4 Method ....................................................................................................................... 16

4.1 Literature search method ...................................................................................... 16

4.2 Selection of literature returned during search .................................................... 17

4.3 Evaluation of validity and reliability .................................................................... 18

4.4 Method of analysis ............................................................................................... 19

5 Results ...................................................................................................................... 20

5.1 Presentation of the literature searches .................................................................. 20

5.1.1 Search 1 ........................................................................................................ 20

5.1.2 Search 2 ........................................................................................................ 20

5.1.3 Search 3 ........................................................................................................ 21

5.1.4 Search 4 ........................................................................................................ 21

5.1.5 Search 5 ........................................................................................................ 22

5.1.6 Articles found in the references section of other articles ......................... 22

5.2 Articles excluded from analysis .......................................................................... 23

5.2.1 Search 1 ........................................................................................................ 23

5.2.2 Search 2 ........................................................................................................ 24

5.2.3 Search 3 ........................................................................................................ 25
5.2.4 Search 4. .................................................................................................................. 26
5.2.5 Search 5. .................................................................................................................. 27

5.3 Articles included for analysis .................................................................................. 28
5.3.1 Summary of the articles included for analysis ..................................................... 29
5.3.1.1 Learners’ Mental Models of the Particle Nature of Matter: A study of 16 - year - old Swedish science students. ........................................................................................................ 29
5.3.1.2 Why Do We Believe that an Atom is Colourless? Reflections about the Teaching of the Particle Model .................................................................................................................... 32
5.3.1.3 Secondary Students’ Mental Models of Atoms and Molecules: Implications for Teaching Chemistry .......................................................................................................................... 35
5.3.1.4 Why we should teach the Bohr model and how to teach it effectively .................. 36
5.3.1.5 Identifying Atomic Structure as a Threshold Concept: Student mental models and troublesomeness. .................................................................................................................. 40
5.3.1.6 Atomic Orbitals, Molecular Orbitals and Related Concepts: Conceptual Difficulties Among Chemistry Students ........................................................................................................... 41
5.3.1.7 Examining Pre-Service Teachers’ Use of Atomic Models in Explaining Subsequent Ionisation Energy Values .................................................................................................................. 43
5.3.1.8 Conceptualizing quanta: Illuminating the ground state of student understanding of atomic orbitals ................................................................................................................................. 44
5.3.1.9 Atomic orbitals and their representation: Can 3-D computer graphics help conceptual understanding? .................................................................................................................. 46
5.3.1.10 The Chocolate Shop and Atomic Orbitals: A New Atomic Model Created by High School Students to Teach Elementary Students ........................................................................... 48

6 Discussion ................................................................................................................... 51
6.1 Discussion of obtained results .................................................................................. 51
6.1.1 What models, representations and simulations are used to teach the atom and atomic concepts in the science classroom? .................................................................................. 51
6.1.2 How do learners interpret different representations of the atom, and what mental models do student construct and use to understand the atom? .................................. 52
6.1.3 How can the representations be used and designed for meaningful learning and teaching of the atom and atomic concepts? .......................................................................................... 55
6.2 Discussion of methods used to locate and analyse the literature ......................... 57
6.3 Evaluation of the quality of the articles included for analysis ............................... 58
6.4 Conclusions ............................................................................................................. 64
6.5 Implications for further research ........................................................................... 65

7 References .................................................................................................................. 67
7.1 Acknowledgement of sources for figures ................................................................. 70
1 Introduction

This report presents a study conducted as a part of the Upper Secondary School Teacher Programme at Linköping University. The study is a systematic literature review on the role of models and representations in the teaching, learning and understanding of the atom and atomic concepts.

Atomic and orbital concepts are abstract and difficult for students to understand. Since atoms cannot be observed with the naked eye, students often have difficulties visualizing atomic phenomena. Therefore, models and representations are necessary tools for science education, and if understood and used meaningfully can help improve students’ learning.

Several different models are used in classrooms and in textbooks to teach the atom and related atomic concepts, such as static 2-D pictures, animations, 3-D simulations and virtual reality environments. The aim of this study is to investigate what models and representations are used in school to teach the atom and atomic concepts, what mental models students use to describe the atom and how the representations can be used and designed to support effective and meaningful learning of the atom and atomic concepts.

This study was carried out as a systematic literature review. The databases ERIC, Scopus and, to some extent, Google Scholar were used to locate and synthesize research that has been conducted in relation to the posed questions.
2 Aim of the study

The aim of this study is to investigate the role of different visual representations in the teaching, learning and understanding of the atom and related atomic concepts. More specifically the following questions were raised:

- What models, representations and simulations are used to teach the atom and atomic concepts in the science classroom?
- How do learners interpret different representations of the atom, and what mental models do students construct and use to understand the atom?
- How can the representations be used and designed for meaningful learning and teaching of the atom and atomic concepts?
3 Background

In this section definitions pertinent to the topic under study as well as the underpinning theoretical framework will be presented. In the first subsection, definitions of concepts used in this study are listed, with the purpose to support the reader. In the second subsection, the theoretical framework of the study is presented.

3.1 Definitions

Atomic model: Theoretical model for describing the structure of the atom (Nationalencyklopedin). For example Bohr’s, Thomson’s, Rutherford’s and Schrödinger’s respective model of the atom. Examples of teaching models to describe the atom are the solar system model (Harrison & Treagust, 2000a).

Dynamic linking, dyna-linking: When a change in one representation results in change in another representation. The actions of the user evoked during these changes help translation between different representations (Ainsworth, 2006).

External representation: The knowledge and structure in the environment represented as external rules and symbols (Zhang, 1997). Examples of external representations are tables, diagrams, pictures and simulations.

Representation: An illustration or example of something else (Gärdenfors, n.d.).

Mental model: Models that students themselves create to describe reality (Harrison & Treagust, 2000a). These models vary among students, and they are not always correct but they must be functional for describing the phenomenon (Harrison & Treagust, 1996).

Model: A representation of a phenomenon, e.g. a model of the atom (Linn, Stenbom, & Prawiz, n.d.).

Multimodal learning environments: Learning environments that use both verbal and non-verbal modes to communicate knowledge (Moreno & Mayer, 2007).
Multiple external representations (MERs): A combination of more than one different external representations, such as tables, diagrams, pictures, simulations e.g. that depict a phenomenon (Ainsworth, 2006). Usually more than two representations are used.

Representational competence: The ability to transform the representational expression of one situation or concept from one form to another (Kozma & Russel, 1997).

Scientific modelling: “The generation of a physical, conceptual, or mathematical representation of a real phenomenon that is difficult to observe directly” (Rogers, n.d.)

Scientific visualization: To graphically display scientific data (Encyclopaedia Britannica, 2013).

Translation: To see relations and connections between different representations (Ainsworth, 2006). This can be difficult for students, and therefore support can be provided in the representations, e.g. dynamic linking (see definition above).

3.2 Theoretical framework

According to the Swedish school curriculum programme for the course Physics 2 (Skolverket, 2011), teaching content should cover:

- The electron structure of atoms, and absorption and emission spectra.
- (...) Models and theories as simplifications of reality. Models and their areas of applicability and how they can be developed, generalised or replaced by other models and theories over time.
- The importance of experimental work in testing, re-assessing and revising hypotheses, theories and models (Skolverket, 2011, p 14).

Incorporated as an aim for teaching the subject, students should be given an opportunity to use computerized equipment for learning, which supports the use of simulations and visualisations to help understanding physical phenomena.
3.2.1 Role of models in science education

Models are effective tools for teaching science, since they can enhance understanding, communication and investigation of scientific phenomena among learners (Harrison & Treagust, 2000a). Models can be used to communicate abstract phenomena and present aspects of scientific experimentation that would otherwise be unfeasible to perform in the classroom. Models are easy to access and students often appreciate this way of learning. Since many scientific concepts are beyond our perceptual experience, we require models to communicate abstract knowledge. Furthermore, models offer one way of making science education more authentic (Gilbert, 2004).

Analogical models are models that share information with the phenomenon that they describe. They represent one or several attributes of the target (Harrison & Treagust, 1996). They can be concrete, such as scale models, or more abstract, such as a scientific model of the atom (Harrison & Treagust, 2000a). When used to teach concepts in science, analogical models are termed “pedagogical analogical models”. Examples of pedagogical analogical models are symbolic models, such as chemical formulae and equations, mathematical models and theoretical models. Some models can be used to teach more than one concept at a time, e.g. the periodic table. Models can also be used to describe processes, e.g. chemical reactions. For example, a chemical reaction itself is immaterial, but it is easier for the students to think of it in concrete terms (Harrison & Treagust, 2000a). Furthermore, a simulation can effectively represent complex dynamic processes, such as nuclear reactions, that may be difficult to convey with a static 2-D representation.

An example of an analogical model of the atom is the solar system model. Harrison and Treagust (2000a) describe this as an “extended model” since there is more than one analogical model that describe the target. By analogy, the nucleus is represented by the sun, and the electrons are represented by the planets. The electrons orbit the nucleus, just as the planets orbit the sun. The nucleus and the electrons attract each other, and the same is true for the sun and the planets. Furthermore the atom consists mostly of space, just as the solar system. However, there are some attributes that are not shared between the solar system and the atom. For example the orbits in the solar system are elliptical while the orbits in the atom are not, and the planets are differ in size while the electrons do not. In the solar system there is just
one planet per orbit, but there are multiple electrons per level in the atom (Harrison & Treagust, 2000a).

The models that students create themselves to describe reality, are called “mental models” (Harrison & Treagust, 2000a). These models vary among students, and they are not always correct but they must be functional for describing the phenomenon (Harrison & Treagust, 1996). According to Gilbert (2004), all students in chemistry and physics have a mental model of the atom. A student’s mental model can be influenced when a teacher presents scientific models that describe the phenomena in different ways. The new models are called “synthetic models” (Harrison & Treagust, 2000a). When the mental model is expressed to others, it becomes an “expressed model”, and when more than one person agrees on a model, it becomes a “consensus model” (Gilbert, 2004). Other kinds of models are “scientific models” and “historical models”. A scientific model of the atom is the Schrödinger model, and the Bohr model would be considered a historical model. Furthermore, special “teaching models” can be used to teach a phenomenon, such as using the solar system model to describe the atom.

3.2.2 Difficulties when interpreting and using models

According to Harrison & Treagust (2000a), secondary school students tend to believe that only a single model is appropriate for representing all the attributes of a phenomenon (Harrison & Treagust, 2000a). For example, the shell model is a popular representation among student to describe the atom. Although research has shown that students can learn to use multiple representations to describe a phenomenon, and as a consequence they discover that no model is completely correct (Harrison & Treagust, 2000a). In an article about different representations in chemistry, Hoffman and Laszlo (1991) eloquently express this notation:

But let’s stop and ask: Which of these representations, (...), is right? Which is the molecule? Well, all are, and none is. Or, to be serious – all of them are models, representations suitable for some purposes, not for others (Hoffmann & Laszlo, 1991, p. 5).

Given the above, students often find it difficult to select appropriate analogies, models and representations to describe a phenomenon (Harrison & Treagust, 2000a). Therefore it is important to explicitly teach how to use analogies and models in school. For example, the
models must be appropriate for the students, in terms of prior knowledge level. When using analogies to teach scientific phenomena, it is important for teachers to reflect upon how the students might interpret them (Harrison & Treagust, 1996). It is a common finding that students interpret the teacher’s analogies erroneously or too literally, with the consequence that they create scientifically incorrect mental models of their own.

3.2.3 What are the purposes, uses and functions of multiple representations in communication of scientific concepts?

According to Ainsworth (1999), external multiple representations (MERs) have several different functions, and can be used in many aspects of teaching. She suggests that there are three overall main functions of MERs, namely:

1. Complementary roles
2. Constraining interpretations
3. Constructing deeper understanding

Complementary roles

Different representations have different functions that support students learning in different ways, and the different representations can therefore complement each other (Ainsworth, 1999). MERs can be used to support complementary processes as well as to support complementary information. Single representations may have both strengths and weaknesses, but by combining representations the processes can complement each other and make up for these weaknesses. Different representations can support the learner in different ways, even though they describe the same concept and contain equivalent information. As an example, Ainsworth (1999) compares describing variation with an equation and a graph. The graph succeeds in describing the variation more explicitly and directly than the equation does, even though they describe the same thing and contain equivalent information. In the same way, a table is effective for identifying specific values in an explicit way. It follows, that a combination of representations of the processes, e.g. a table, an equation and a graph, might be successful for interpreting a situation since each of the respective representations highlights different aspects of the situation. Consequently, information obtained from each individual representation, can be combined to provide a rich overall picture.
Since pupils are unique individuals that learn in different ways, they can profit cognitively and conceptually from working with different representations, since they have the opportunity to choose the representation that they prefer (Ainsworth, 1999).

Different representations could also contain different information, and by working with multiple representations they can complement each other. It has been shown that it is effective to divide information across two representations, since it allows the pupils to focus on different parts of the problem (Ainsworth, 1999).

Another benefit of working with multiple representations is that it encourages learners to use more than one strategy to solve a problem (Ainsworth, 2006). This is often encouraged in mathematics, by working with so called “rich mathematical problems” which allows students to use a number of different strategies and approaches to solve a problem (Hagland, Hedrén, & Taflin, 2005).

**Constrain interpretations**

Multiple representations can also be used to help pupils understand new representations by combining them with familiar representations that contain equivalent information (Ainsworth, 1999). For instance, if, pupils are given two representations where one is familiar, they can use the one they understand to assist in interpreting the functions of the other. As well as complementing processes, combining multiple representations can also help to complement information. For example, a common misunderstanding among students is that a horizontal line in a velocity-time graph corresponds to a stationary object (Ainsworth, 1999). By combining an animation and a graph, where the graph is generated as consequence of the motion in the animation, students’ understanding can be supported. In this case, when an object moves with a constant speed in an animation, a horizontal line in the velocity-time graph will be generated, and the students are thus provided with the opportunity to interpret the representation.

**Construct deeper understanding**

Ainsworth (1999) suggests that multiple representations can help construct deeper understanding of a task or phenomenon through:

- supporting abstraction
- supporting extension
Ainsworth (1999) refers to previous research that has shown that interpreting multiple representations makes it possible for pupils to construct a more abstract understanding of a task. As a result of discovering connections between two existing representations, students are able to create a new and more abstract representation. Learning with multiple representations can also support the application of knowledge in another situation. By teaching the relationships between different representations, students learn how to interpret and translate between the representations. Translation between representations is one of the main goals when working with models and representations in the science classroom.

3.2.4 How do learners interpret and understand different representations?

The interplay between students’ internal representations, and external representations is a complex process (Scaife & Rogers, 1996). When a student interprets a representation, some information might get lost when it is integrated with the prior knowledge.

Moreno and Mayer (2007) describes a cognitive-affective theory of learning with media that may present the learner with other kinds of representations than words and pictures, such as virtual reality environments. The theory is based on the premise that humans have different channel modalities for interpreting different modes of information, and that only a limited amount of information can be processed in each channel at any one time. Hence, if instructional material from a representation overwhelms the learners’ cognitive resources, learning will be hindered (Cook, 2006).

Learning becomes meaningful when the learner consciously selects and organizes information and integrates it with excising knowledge (Moreno & Mayer, 2007). A student’s prior knowledge will affect what will be learned from a specific representation. Students’ prior knowledge influences their attention and perception, and since learners use their prior knowledge when selecting information from representations, the mental models they create will depend on their existing knowledge (Cook, 2006). Therefore, mental models will vary among students.
When students work with multiple models, they need to create a mental model by organizing the representations that are provided (Moreno & Mayer, 2007). The information in the multiple models needs to be organized and integrated with the knowledge, and this can be supported by feedback embedded in the interactive learning environment. Overall, learning is most effective when the students are able to use metacognition and reflect upon their own cognitive limitations and strengths.

3.2.5 How are multiple representations designed to support effective learning?

The design of representations will have an influence on what pupils will learn and how effective the learning process will be (Ainsworth, 2006). Both what information the representation should contain and the way the information should be presented needs to be taken in consideration when designing multiple representation systems. Ainsworth (2006) mentions five design dimensions that must be considered when designing systems of multiple representations:

1) *The number of representations*. A system of multiple representations should consist of more than two representations.

2) *How the information is distributed between the representations*. The representations can contain completely different information, which requires the learner to find new representations to connect them. A second approach is to use representations that share some information. As a final approach, the representations can contain the same information, but the way the information is presented differs.

3) *What form the representational system has*, e.g. text, pictures, simulations, animations, graphs and so on.

4) *In what sequence the representations should be presented*. In what order the learner should add a new representation, if they are not used at the same time.

5) *How translation between representations should be supported*. The support can be presented on different levels, such as at surface- or deep level, representational or domain levels (Ainsworth, 2006).

What students learn from working with multiple representations does not only depend on effective design. Pupils’ learning will also depend on their previous knowledge and their learning goals (Ainsworth, 2006). Therefore, the representations can be used in different ways to support different aspects of learning.
The notion of a representation should be easily understandable, and the visual organization that is used to structure them should be appropriate, e.g. static- or dynamic diagrams (Scaife & Rogers, 1996). Regarding interactive multimodal learning environments, Moreno and Mayer (2007) suggests five design principles: guided activity, reflection, feedback, pacing and pretraining. Guided activity posits that the students’ cognitive processing is guided by pedagogical agents, which will improve learning. It is also important that the learning environment asks students to reflect upon their answers, since it encourages more active knowledge organization. Students should also be provided with explanatory feedback, which reduces extraneous processing. Students should be able to control the pace of the presentation, since only limited chunks of knowledge can be processed in the working memory at a time. Pretraining helps the learner by indicating what prior information that should be integrated with newly processed information.

3.2.5.1 Translating between more than one representation
An important aspect that needs to be taken into consideration when designing systems of multiple representations is how support should be provided for students to help them translate between representations. According to Ainsworth (2006) previous research in the field has demonstrated that many learners find such translation demands difficult. Therefore, including different kinds of implicit cues in the representations serves as a way to support the translation process (Ainsworth, 2006). As an example, the same colours can be used to represent the same thing in different representations, which can help pupils see connections more explicitly. Dynamic linking is another example, where a computer makes the translation between representations. The learner can change something in one representation, and then see the results of his or her actions in another representation. The learners can observe what happens and hopefully understand and learn the connection between the representations and the presented phenomenon. Although Ainsworth (2006) also suggests that the learners level of background knowledge will determine in what way they will benefit from the support. The support should be given in different ways depending on the learner. The representations are most effective if they are simple and concrete, and representations must be chosen with the learner and the situation taken in consideration.

In a study by Kozma and Russel (1997), the ability to make transformations between different forms of representations among experts and novices was examined. Five males and five
females, (all 18-19 years old), represented the novices, and had all studied their first chemistry course at the university, and they all had previous knowledge in chemistry since high school. There were 11 experts – five professional chemists, five doctoral students and one chemistry faculty member from a community college. In the experiment the participants were given 15 representations on a computer screen. For some representations they were asked to find a corresponding representation among the representations on the screen, and for some representations they were asked to generate a corresponding representation of their own. The results showed that novices found it much more difficult than experts to make transformations between representational forms, when they were asked to generate a corresponding representation such as a graph or an equation. They found it especially difficult when translation should be made from an animation or a video to another representational form. The knowledge of novices often consists of unconnected fragments. However, experts use a more hierarchical structure of knowledge to understand chemical phenomena. The experts can see the same situation being represented by different types of representations, and they have the ability to make transformations between different representational forms depending on the specific requirements of the task. This ability is called “representational competence” (Kozma & Russel, 1997).

The atom is an example of an abstract entity that can be represented with several different models.

3.2.5.2 Constructivism and learning science

Constructivism is a view of learning that emphasizes the active role of the learner in understanding information (Woolfolk, 2010). There are two central ideas in constructivism. Firstly, learners play an active role in constructing their own knowledge. Secondly, social interactions are important for the knowledge construction process. Psychological constructivism is based on the ideas of Piaget, and focuses on the individual and psychological sources of knowing. The theory is concerned with how individuals make sense of the environment based on their unique individual knowledge. Social constructivism is based largely on Vygotsky’s theory, and focuses on the cultural and social sources of knowing. According to this theory, the social interaction and activity shape individual learning and development.
The constructivist perspective of learning has been very influential in science education (Taber, 2003). Research has shown that the most important fact is that students have ideas to develop, rather than that the ideas are scientifically correct. When teaching new and abstract scientific concepts, it is important that the teacher finds ways to connect the new information to students’ previously existing knowledge. This can be done using appropriate analogies and metaphors, which allow the students to make sense of information in a context that they are already familiar with.

3.2.6 Models to describe and represent the atom

The atomic concept is central in chemistry and in physics, and is a core aspect in science education (Taber, 2003). However, conceptualising the idea of the atom has shown to be demanding for learners. The models of the atom that are taught in school are often different from the scientific ideas of the atom, and they may also be different from the models that are most effective from a pedagogical point of view (Taber, 2003).

Since atoms and molecules are too small to be observed, models are necessary for describing and communicating changes in matter at particle level (Harrison & Treagust, 1996). However, the large amount and variety of different models and analogies for communicating atomic phenomena can be demanding for the learners.

3.2.6.1 Historic models to describe the atom

Initially atoms were described as simple spheres. In the mid 19th century, the electron was discovered by Thomson (Lindgren, n.d.). Since he knew that the electron was negatively charged, and that the atom was neutral, he drew the conclusion that the atom must consist of electrons embedded in a positively charged mass. This line of reasoning is sometimes represented as the “plum-pudding-model” of the atom (Figure 1).
In the early 20th century Rutherford conducted experiments with alpha rays. He allowed a thin ray of alpha particles to strike a thin gold foil, and he noticed the scattering of the alpha particles. The scattering angle of the particles indicated that the positive charges in the atom must be concentrated in a centre, like a nucleus. This discovery gave rise to the solar system model of the atom (Figure 2), which is more similar to the atomic models that we use today (Lindgren, n.d.).

Around the same time as Rutherford performed his alpha ray experiments, quantum theories of physics started to develop to explain the physical phenomena that classical mechanics could not. According to classical electrodynamics, the electrons in the solar system model would eventually fall into the nucleus of the atom as a result of the loss of energy caused by the emission of radiation. In 1913 Niels Bohr presented a new model of the atom. Although, related to the solar system model, electrons were now modelled as being located in specific orbits depending on their energy level. The electron only emits radiation if it drops to a lower energy level, and it absorbs radiation if it jumps up to a higher energy level. This theory made the atom more stable, so that the electrons would not be subsumed into the nucleus (Lindgren, n.d.).

In 1924 Louis de Broglie presented the theory of the wave property of matter. He assumed that electrons move like waves in the atom, and that the stable states answer to complete wavelengths (Andersson, n.d.). This led Erwin Schrödinger into working with wave mechanics, and he presented the Schrödinger equation in 1926. In the Schrödinger model of the atom (Figure 3), every electron has a set of quantum numbers that describe it’s state in the atom.
3.2.6.2 Students' conceptions of the atom

Models are attractive to students, since they can communicate abstract concepts in familiar and visually meaningful ways (Harrison & Treagust, 2000b). Students prefer to think of abstract processes in concrete terms, but as their knowledge is developed, they are often reluctant to replace their already developed models with more scientifically correct ones.

Students often find concepts of atomic structure difficult and confusing (Taber, 2003). In this regard, Taber (2003) distinguishes between two classes of misconceptions of the atom among students that are scientifically incorrect. Firstly there are some students who have an insufficient understanding of particle related ideas, which may lead to confusion of labels on diagrams since they cannot differentiate between the different concepts. Secondly there are students that have a sufficient understanding of the particle concept, but have difficulties understanding how the particles interact. For example, students may think that the neutrons in the nucleus neutralize the charge of the protons, rather than having a neutral charge. According to Taber (2003), students do not automatically relate electrostatic principles that they have learned in physics to a chemistry domain. For example, there are students who believe that the atom is indivisible when learning chemistry, even though they have accepted the concept of radioactive decay in physics.

Another misconception among students is that the nucleus is held together by electrons pushing upon it (Taber, 2003). This suggests that the electrons and the protons would repel each other, which is scientifically incorrect.

The belief that the atom is indivisible is common among students (Taber, 2003). This way of thinking occurs, not only among students who have an insufficient knowledge of the structure of the atom, but also among students who are not ignorant of subatomic particles. It is a common conception that electrons belong to a specific atom, which may lead to misconceptions concerning molecular bonding. Learning about atomic structure is often a difficult assignment for many students (Harrison & Treagust, 2000b).
4 Method

This study was carried out in the form of a systematic literature review. The aim of a systematic literature review is to locate and synthesize research performed in the relation to the questions raised by the study (Forsberg & Wengström, 2008). Since it is often practically impossible to include all research conducted within a field, it is necessary to develop suitable and valid criteria for inclusion and exclusion of studies reported in the literature. It is also important that the emergent articles correspond to the defined aim and posed questions of the literature study.

Give the above, Forsberg & Wengström (2008) have outlined eight steps that describe the procedures for performing a systematic literature review:

1. Formulate the aim of the study, and justify why the study should be conducted
2. Formulate questions that can be answered
3. Make a plan for the study
4. Select appropriate search words and a search strategy
5. Identify and select literature
6. Critically evaluate and select which articles should be included
7. Analyse the articles and discuss the results
8. Summarize the results and draw conclusions

The methods for the literature search, the selection of literature, the evaluation of quality and the analysis are presented in the subsections below.

4.1 Literature search method

To increase the identification of articles in line with the aims of the current study, a combination of different databases was used to search for literature, namely ERIC, Scopus and Google Scholar. ERIC is a specialized database covering educational science and psychology. Since this study is focused on the domain of physics education, suitable articles would potentially be identified through this database. Articles about learning and teaching the atom, that are published in non-educational journals and will not be listed in ERIC, so Scopus, was used as an additional database to cover these articles as well as uncover other
educational-related physics and chemistry sources perhaps not listed in ERIC. Scopus is a database covering all subjects, and might contain articles about physics and chemistry that could assist in responding to the questions of this study. To ensure as many valid peer-reviewed academic articles as possible were identified, Google Scholar was also used as a third database to complete the searching coverage to a wide degree and pick up any meaningful articles that may have been inadvertently missed.

To find articles suitable for this study, a set of search words and search strings were constructed for deployment in the database search. Search words were combined into different search strings. The Boolean operators “AND”, “NOT” and “OR” were used. Supposing that we have two search words A and B, “A AND B” will return sources that contain both A and B. Using “A NOT B” will return sources that contains A but not B. Lastly, “A OR B” will provide sources that contains A or B (Forsberg & Wengström, 2008). In summary, “AND” and “NOT” are used as operators to narrow down the result of a search, while “OR” widens it. In addition, truncation was used to widen the result of the searches. In this case truncation involves replacing the end or beginning of a word or term with an asterisk (*), which allows the search to return articles that contain different versions of an inputted word (Forsberg & Wengström, 2008). For example, searching for the word “atom*” will return articles that also include for example “atoms” and “atomic”, and searching “teach*” will return “teach”, “teaching”, “teacher” and so on.

In addition to the articles found during the searches, three other peer-reviewed articles were included which were found in the references section of other articles and were meaningful for this study given the posed research questions. These articles are listed in the Google Scholar database.

4.2 Selection of literature returned during search

In addition to the combination of search words and the use of Boolean operators, some limiters were used to narrow down the returned results. The articles should be peer-reviewed and be published 1990-01-01 or later. The aim was to find relatively new research, but since few articles focusing on representations of the atom were found, the year 1990 was used as a
limit. In some cases, the searches were narrowed down by subject, such as “nuclear physics” or “models”.

For articles to be included for individual analysis in this study, they should communicate content related to representation of the atom or molecules in combination with pedagogical aspects or issues of learning and/or teaching the atomic-related phenomena. Articles that were searched for addressed students’ perception of the atom, how students learn about the atom, what visualisations/representations/models are used in science education to teach the atom, and students’ alternative conceptions of atomic phenomena. Therefore, at the outset, search words including “atom*”, “model*”, “represent*”, “mental models”, “concept*”, “visual*”, “student*” and “teach*” were used in different combinations. The search strings will be presented in the results section (chapter 4) of this study. Settings were adjusted so that the searches would locate articles that contained the search words in the title, abstract or in the text. The abstract of the articles were read, and if they seemed relevant to the questions of this study, they were included and analysed individually. In some cases, where information in the abstract was insufficient, the full text was also consulted to decide whether to warrant inclusion of not. When the final articles for synthesis were selected, the full texts were consulted and read in full, and an evaluation of the validity and reliability was made (see section “Evaluation of validity and reliability”).

### 4.3 Evaluation of validity and reliability

To be able to generalise the findings of the result articles, the methods for data collection presented in the articles should have a high level of validity and reliability (Forsberg & Wengström, 2008).

If a measuring method has a high validity, it should measure what is aimed to measure (Forsberg & Wengström, 2008). For example, the measuring instrument should contain relevant questions for the study, and the questions should be answered with an appropriate method.

If a measuring method has a high reliability, it should be possible to reproduce the measurements and obtain the same results (Forsberg & Wengström, 2008). If the reliability is low, the measurement might provide different results if, for example, the formulations of the
questions in a questionnaire are unclear. For example, the number of participants in a study affects the reliability as well as the time the study was conducted and its geographical context.

The reliability of a study also depends on the method of the study. Studies with small sample sizes can have a high reliability if the method is appropriate. For example, a study carried out by interviewing individual students, might have a high reliability even though the number of participants in the study is low (Forsberg & Wengström, 2008).

Forsberg and Wengström (2008) suggest a number of criteria that should be fulfilled for the articles to be included in the study. In this study, a selection of these criteria was used to evaluate the quality of the selected articles.

- Is the aim and question of the study clear, and is the study designed so that the questions could be answered?
- Is the number of participants in the study high enough?
- Are the measurement methods of the studies adequate, and have the questions been answered?

An evaluation of the quality of the articles included for analysis will be presented in the method discussion (section 6.2).

4.4 Method of analysis

In a systematic literature review, meta-analysis is often a preferred method for analysing the included articles (Forsberg & Wengström, 2008). When using meta-analysis, the results from qualitative studies are combined or contrasted with the aim of finding patterns. The analysis and synthesis of qualitative studies are called meta-syntheses (Forsberg & Wengström, 2008). The different studies are analysed separately, and the findings are then compared to the other articles and discussed in a view of the theoretical background, as well as in terms of the aim and the questions of the systematic review.
5 Results

In this section, the literature searches will firstly be presented. Five searches were made, and the search strings and the number of hits for each of the searches will be presented. Secondly the excluded articles are presented together with the reasons for exclusion. Lastly, the included articles are presented and summarized individually.

5.1 Presentation of the literature searches

5.1.1 Search 1

Search 1 was conducted with ERIC (Table 1).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Number of hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(visual*) AND (atom*)</td>
<td>42</td>
</tr>
<tr>
<td>(visual*) AND (atom*) AND (model*)</td>
<td>19</td>
</tr>
<tr>
<td>(visual*) AND (atom*) AND (model*) AND (student*)</td>
<td>9</td>
</tr>
</tbody>
</table>

5.1.2 Search 2

Search 2 was conducted with ERIC (Table 2).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Number of hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(atom*) AND (model*) AND (simulation* OR representation*) AND (teach*)</td>
<td>16</td>
</tr>
<tr>
<td>(atom*) AND (model*) AND (simulation* OR representation*) AND (teach*) +narrow by subject: &quot;models&quot;</td>
<td>10</td>
</tr>
<tr>
<td>(atom*) AND (model*) AND (simulation* OR representation*) AND (teach*) +narrow by subject: &quot;models&quot; and &quot;teaching methods&quot;</td>
<td>7</td>
</tr>
</tbody>
</table>
5.1.3 Search 3

Search 3 was conducted with ERIC (Table 3).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Number of hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(atom*) AND (&quot;mental models&quot;) AND (student*)</td>
<td>11</td>
</tr>
<tr>
<td>(atom*) AND (&quot;mental models&quot;) AND (student*) + narrow by subject: &quot;models&quot;</td>
<td>5</td>
</tr>
</tbody>
</table>

5.1.4 Search 4

Search 4 was conducted with Scopus (Table 4).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Number of hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(atom*) AND (structure* OR model* OR represent*) AND (student) AND (learn* OR understand*)</td>
<td>340</td>
</tr>
<tr>
<td>(atom*) AND (structure* OR model* OR represent*) AND (student) AND (learn* OR understand*) AND simulation</td>
<td>38</td>
</tr>
<tr>
<td>(atom*) AND (structure* OR model* OR represent*) AND (student) AND (learn* OR understand*) AND simulation + limit to subject area: “chemistry” and “physics and astronomy”</td>
<td>14</td>
</tr>
<tr>
<td>(atom*) AND (structure* OR model* OR represent*) AND (student) AND (learn* OR understand*) AND simulation + limit to subject area: “chemistry” and “physics and astronomy” + limit to document type: “articles”</td>
<td>7</td>
</tr>
</tbody>
</table>
5.1.5 Search 5

Search 5 was conducted with ERIC (Table 5).

Table 5: Number of hits in ERIC when specifying the search strings in search 5.

<table>
<thead>
<tr>
<th>Search string</th>
<th>Number of hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(atom*) AND (representation*) AND (student*) AND (understand*)</td>
<td>14</td>
</tr>
<tr>
<td>(atom*) AND (representation*) AND (student*) AND (understand*) AND (&quot;concept formation&quot;)</td>
<td>4</td>
</tr>
</tbody>
</table>

5.1.6 Articles found in the references section of other articles

The peer-reviewed articles presented in table 6 were found in the references section of other articles and during searches, and could be found in Google Scholar. Reasons for inclusion are also presented (Table 6).

Table 6: Articles found in the references section of other articles, and reason for inclusion.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author(s) (year)</th>
<th>Reason for inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptualizing quanta: Illumination the ground state of student understanding of atomic orbitals.</td>
<td>Taber, K.S., (2002)</td>
<td>The article discusses student understanding of atomic orbitals, which is relevant for this study.</td>
</tr>
<tr>
<td>The Chocolate Shop and Atomic Orbitals: A New Atomic Model Created by High School Students to Teach Elementary Students.</td>
<td>Liguori, L. (2014)</td>
<td>Describes a new atomic orbital model created by students for students. Limitations and advantages of the model are discussed. Relevant to the aims of the current study.</td>
</tr>
</tbody>
</table>
5.2 Articles excluded from analysis

In Table 8-12 below, the excluded articles, and the reasons for exclusion from searches 1-5 are presented.

5.2.1 Search 1

Search 1 was made in ERIC (Table 7).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Title</th>
<th>Author, (year)</th>
<th>Reason for exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(visual*) AND (atom*) AND (model*) AND (student*) AND (understanding)</td>
<td>Using Molecular Models To Show Steric Clash in Peptides: An Illustration of Two Disallowed Regions in the Ramachandran Diagram</td>
<td>Halkides, C. J. (2013)</td>
<td>This teaching model can be used as a tool in biochemistry to teach and help students understand protein structures. Does not focus on representations of the atom.</td>
</tr>
<tr>
<td></td>
<td>Making It Visual: Creating a Model of the Atom.</td>
<td>Pringle, R. M. (2004)</td>
<td>Describes a lesson in which students get to construct Bohr model of the atom. The author writes about the possible profits from working with models, but the article does not provide any research results on how students learn with representations of the atom.</td>
</tr>
<tr>
<td></td>
<td>Understanding Chemical Reaction Kinetics and Equilibrium with Interlocking Building</td>
<td>Cloonan, C. A., Nichol, C. A., &amp; Hutchinson, J. S. (2011)</td>
<td>About chemical reaction kinetics and equilibrium to help students visualize a simple reaction at the molecular level using small, plastic brick interlocking</td>
</tr>
</tbody>
</table>
Blocks

Near-Field Imaging with Sound: An Acoustic STM Model.
Euler, M. (2012)

Presents a model of scanning tunneling microscopy, and how it can be used to make quantum concepts such as tunneling less abstract to students. Focus is not on representations of the atom.

Modelling Photosynthesis to Increase Conceptual Understanding

Is about biology and how to model photosynthesis to increase conceptual understanding. I want to focus on representations of the atom within the areas of physics and chemistry.

Confirming the 3D Solution Structure of a Short Double-Stranded DNA Sequence Using NMR Spectroscopy.

Is about confirming the 3D Solution Structure of a Short Double-Stranded DNA Sequence Using NMR Spectroscopy. I want to focus on models of the atom, in physics or chemistry.

5.2.2 Search 2

Search 2 was made in ERIC (Table 8).

Table 8: Excluded articles from search 2

<table>
<thead>
<tr>
<th>Search string</th>
<th>Title</th>
<th>Author, (year)</th>
<th>Reason for exclusion</th>
</tr>
</thead>
</table>
Student Misapplication of a Gas-Like Model to Explain Particle Movement in Heated Solids: Implications for Curriculum and Instruction towards Students' Creation and Revision of Accurate Explanatory Models.


Focuses of the particle nature of matter. Does not focus on representations of the atom.

Current Density and Continuity in Discretized Models.


Mathematical models of the Schrödinger equation. I want to focus on representations of the atom.

Making Ordered DNA and Protein Structures from Computer-Printed Transparency Film Cut-Outs.


Is about making models of DNA structures. Does not focus on representations of the atom.

5.2.3 Search 3

Search 3 was made in ERIC (Table 9).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Title</th>
<th>Author, (year)</th>
<th>Reason for exclusion</th>
</tr>
</thead>
</table>
5.2.4 Search 4

Search 4 was made in Scopus (Table 10).

Table 10: Excluded articles from search 4

<table>
<thead>
<tr>
<th>Search string</th>
<th>Title</th>
<th>Author, (year)</th>
<th>Reason for exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(atom*) AND (structure* OR model* OR represent*) AND (student) AND (learn* OR understand*) AND simulation + limit to subject area: “chemistry” and “physics and astronomy” + limit to document type: “articles”</td>
<td>11th IAEA technical meeting on H-mode physics and transport barriers</td>
<td>Takizuka, T. (2008)</td>
<td>From a conference. Does not focus on how students learn representations of the atom, or how to teach it effectively.</td>
</tr>
<tr>
<td></td>
<td>Intermolecular forces as a key to understanding the environmental fate of organic xenobiotics</td>
<td>Casey, R.E., Pittman, F.A. (2005)</td>
<td>Does not focus on representations of the atom. Requires background knowledge of atoms and bonds.</td>
</tr>
<tr>
<td></td>
<td>Teaching Diffraction with the Aid of Computer Simulations</td>
<td>Neder, R.B., Proffen, Th. (1996)</td>
<td>Is about a computer simulation that can help students understand diffraction of atoms. It does not focus on representations of the atom.</td>
</tr>
</tbody>
</table>
Learning science through guided discovery: liquid water and molecular networks

Ostrovsky, B., Poole, P.H., Sciortino, F., Eugene Stanley, H., Trunfio, P. (1991) Is about learning with multiple representations, but focuses on molecular bonding. I want to focus on representations of the atom.

5.2.5 Search 5

Search 5 was made in ERIC (Table 11).

<table>
<thead>
<tr>
<th>Search string</th>
<th>Title</th>
<th>Author, (year)</th>
<th>Reason for exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baroque Tower on a Gothic Base: A Lakatosian Reconstruction of Students’ and Teachers' Understanding of Structure of the Atom.</td>
<td>Blanco, R., &amp; Niaz, M. (1998)</td>
<td>Does not focus on how representations of the atom can be used for teaching or how they can help students understand.</td>
</tr>
<tr>
<td></td>
<td>Near-Field Imaging with Sound: An Acoustic STM Model.</td>
<td>Euler, M. (2012)</td>
<td>Presents a model of scanning tunneling microscopy, and how it can be used to make tunneling concepts such as tunneling less abstract to</td>
</tr>
</tbody>
</table>

Table 11: Excluded articles from search 5
students. I want to focus on representations of the atom.

Overall a total of 21 articles were excluded during the searching phase based on the reasons put forward in Table 8-12 above.

### 5.3 Articles included for analysis

In this section, the included articles from the literature searches are presented and summarized. The included articles each correlate meaningfully with responding to aspects of the posed questions of the study. The included articles are first presented Table 12 below, and numbered from 1-10. In the next subsection, the articles are summarized individually.

**Table 12: Included articles from the searches. Ten papers are presented, together with titles, sources and authors.**

<table>
<thead>
<tr>
<th>Number</th>
<th>Title (journal title)</th>
<th>Author, (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Why Do We Believe that an Atom is Colourless? Reflections about the Teaching of the Particle Model. (<em>Science and Education</em>)</td>
<td>Albanese, A. &amp; Vicentini, M., (1997)</td>
</tr>
</tbody>
</table>
5.3.1 Summary of the articles included for analysis

5.3.1.1 Learners’ Mental Models of the Particle Nature of Matter: A study of 16-year-old Swedish science students.

The aim of a study made by Adbo & Taber (2009) was to investigate students’ mental models of the particle nature of matter. The work in this article is part of a longitudinal study about chemical understanding among students. The research was performed from a constructivist view of learning, where the view is that learners create their own unique knowledge. This knowledge is referred to as “mental models”.

Models are an important part of chemistry education, and they can represent phenomena both at the observable macroscopic world as well as the microscopic world, which cannot be observed with the naked eye (Adbo & Taber, 2009). A potential problem with models is that they often are observed as correct and complete representations of reality, and the limitations of models are not always presented to the students. Unawareness of the limitations can be problematic when students create their own mental models of chemical phenomena. Students often have difficulties with connecting the microscopic and macroscopic properties of matter, and Adbo & Taber (2009) draw the conclusion that the difference between the concepts of substance, matter and its forms are difficult for learners of all ages to understand.

The participants of the study that is presented in the article by Adbo & Taber (2009) were students in the beginning of Swedish upper secondary school (16 years old). The teaching models used for teaching the atom to these students are derived from the Bohr model. At the end of compulsory school (ages 7-15) the students was taught about the atom for the first time, and the teaching models used were derived from the Bohr model of the atom. It is not
until university that students learn about the atom at an orbital level. The Bohr model is effective for teaching in that the nucleus consists of protons and neutrons, but when the orbitals are introduced to students, the model is ineffective and can lead to incorrect mental models among students (Adbo & Taber, 2009).

Qualitative interviews were selected as the method for the study to be able to explore how students reasoned about the models (Adbo & Taber, 2009). Eighteen students from two different Swedish schools volunteered to participate in the interviews. The results did not differ between the schools, and the authors of the article therefore suggest that the results could be applicable to other students in the whole country.

The interviews were divided into three sessions (Adbo & Taber, 2009). In the first session the students were asked to draw a model of an atom. The second and third interview was about the phases of matter, and the students were asked questions such as why a liquid is liquid, and the differences between the states of matter. The first interview about the atom was undertaken before the students had been taught the topic at upper secondary level. At the time the other two interviews were held, the students had started the Swedish “Chemistry A” course. Swedish was used as the language for the interviews.

As part of the results of the first interview about the atom, all students used the words “protons”, “neutrons” and “electrons” to describe the subatomic particles of the atom (Adbo & Taber, 2009). The nucleus of the atom was seen as a ball containing protons and neutrons, and 15 of the students believed that the particles in the nucleus did not move at all. A common belief was that the electrons move around the nucleus as planets around the sun, but the nucleus itself remains static. Only two of the students believed that the nucleus exhibited movement, and one of the students explained that the particles moved inside the spherical nucleus like rocks in a rubber ball. Although many of the pictures in textbooks are two-dimensional, many of the students understood that the atom has a three-dimensional structure, and they demonstrated this understanding by forming a sphere with their hands when demonstrating the shape of the atom (Adbo & Taber, 2009).

In all models the students used to represent the atom, the nucleus was over-sized relative to the size of the atom. The reason for this is likely due to the common way textbooks use to represent the atom. Adbo & Taber (2009) think that this does not necessarily mean that
students believe that the proportions in these models are to scale with reality, but it is simply a means of representing it. One student mentioned that the proportions in the model were incorrect and said: “In reality if the nucleus was here then the electrons would be on the other side of the wall (2 metres away)” (Adbo & Taber, 2009, p. 769).

All the students agreed on that the atom is neutrally charged, and it seemed to be more of a central principle rather than a consequence of that the fact that the protons and electrons exert forces on each other (Adbo & Taber, 2009). Since the planetary model is a common way of representing the atom, some of the students believed that the forces between the particles in an atom were the same forces that attract the planets to the sun. Most of the students, however, agreed that the reason for the neutral charge of the atom is that the positive and negative charges of the protons and electrons cancel each other out. The students were aware that the nucleus contains an equal amount of neutrons and protons, and some students mentioned that the neutrons stabilize the nucleus (Adbo & Taber, 2009). Regarding the shells of the atom, half of the students believed that the electron only moved within a shell, while the other half believed that the electrons could move between shells as a result of added energy.

The second interview was about the states of matter. Thirteen of the students believed that the atoms did not move at all in a solid. Some of the students explained the lack of motion with the fact that the atoms are stuck since they are embedded in a solid material. Some of the students, who believed that the atom lacked motion, did believe that the electrons moved within the atom. The students that believed that the atoms had motion found it hard to describe how it was possible for them to move within a solid (Adbo & Taber, 2009). When talking about liquids, many of the students believed that the atoms were “free” without attraction for each other, and that they were embedded within a liquid matter. Many of the students lacked an understanding about the relations between atoms and molecules, and they believed that atoms moved by themselves or in small groups in a liquid. Also in the gaseous state, more than half of the students thought that the atoms moved freely, and that there was no inter-atomic attraction between these atoms.

In the third interview, the effect of heating was discussed. Thirteen of the students saw a relation between the states of matter and temperature. Most of the students believed that when
energy is added to a system the movement of the electrons mainly increases (Adbo & Taber, 2009).

The authors’ interviews revealed the following four conceptions common among students in the study:

1. Atoms are circular with a static nucleus surrounded by moving electrons, and electrons can move within one shell or move between shells due to added energy.
2. There is little internal energy related to the particles. Electronic movement is an exception.
3. The difference between states of matter is caused by a breakdown of structure due to added energy. The added energy increases the movement.
4. Added energy leads to an increase in electronic movement.

The authors suggest that when combining these four conceptions, the students are able to create mental models such as the notion that added heat increases the electronic movement, which causes molecular breakdown (Adbo & Taber, 2009).

The authors also drew the conclusion that the models students drew for representing the atom, parallel those commonly used in textbooks (Adbo & Taber, 2009). The students may not understand that the models are only representational and are not necessary in scale with reality. This can lead to the misconception of an over-sized nucleus. The authors also suggest that teachers should introduce movement in the nucleus when teaching the Bohr model. Many students believe that the nucleus is static, and this makes it more difficult to understand how the atoms can move in a gaseous or liquid state.

5.3.1.2 Why Do We Believe that an Atom is Colourless? Reflections about the Teaching of the Particle Model.

Previous research has shown that students often consider there to be only a scale difference between the microscopic and the macroscopic world, and that the worlds are totally isomorphic in other aspects (Albanese & Vicentini, 1997). A common assumption is that liquids and solids consist of different types of particles, rather than the same particles exhibiting different dynamical properties. To see if these results could be applicable to more students, 30 Italian students at the secondary school (ages 14-16) level were interviewed...
using a questionnaire similar to one used in the previous research. A difference between the questionnaires was that the Italian students in this study were asked about the colour of the atom. The following questions were asked to the Italian students:

- Is it possible to subdivide an object in smaller and smaller particles (infinitely small)?
- What is water made of? And ice?
- What is a molecule?
- Do you think it is possible to see molecules?
- What is the difference between solids and liquids?
- What is an atom?
- What do you think could be the colour of an atom?
- What is your image of an electric current?
- What are the differences between oxygen and hydrogen atoms (Albanese & Vicentini, 1997, p. 253)?

The students in the study were familiar with the words “atom” and “molecule”, and that they have the same properties as the matter that they constitute. The students were also aware that atoms are the smallest parts in which matter can be subdivided. The question about the colour of the atom gave rise to interesting responses. For instance, 80% of the students believed that atoms had a colour, and the colour of the atom corresponded to the colour of the matter the atom was a part of. This showed that students often think that the atoms at the microscopic level behave as matter at the macroscopic level. Only a few students answered that the atom is colourless (Albanese & Vicentini, 1997).

The manner in which teachers’ and textbooks’ represent atoms also affects the students’ understanding of the particle nature of matter (Albanese & Vicentini, 1997). Students often have a common belief that matter is continuous, and when they are told that the structure of matter is discrete, problems occur. It might lead to mental models where the structure of matter is discrete but still continuous. An example of this is the belief that compression of a material means that the individual particles are compressed.

The authors suggest that chemical reactions could be used for explaining the colour of atoms (Albanese & Vicentini, 1997). The difference in colour between reactants and the product of the reaction can be used to prove that atoms do not possess colour. One reason for the common misconception that atoms have colour, could be due to the colourful pictures of atoms communicated in textbooks. Coloured balls are often used to portray the different
atoms in a molecule, and even though this is just a scientific model, students often interpret such representations as reality.

Finding a way for scientists to present scientific theories in physics can be compared to a “modelling game” based on two aspects (Albanese & Vicentini, 1997). First, scientists need to select an appropriate material object for the model, such as a point particle of an incompressible fluid. Secondly, they need to select an appropriate interaction model of different kinds of forces, e.g. pressure or friction. The strategies for creating the models can be demanding to outline, and the interaction between the two kinds of models are often very subtle. Albanese & Vicentini (1997) suggests that there are two kinds of models; primary models and secondary models. A primary model consists of the empirical laws that describe a phenomenon, and a secondary model explains the empirical behaviour. The authors refer to Horton (1982) and present another way to consider this, by referring to primary- and secondary theories. Primary theories are intercultural and functional for everyday life. Secondary theories explain the behaviour in the primary theories, and that hidden entities in the primary theories must be assumed. Secondary theories depend on the social context, but are dependent on the primary theories. The authors suggest that this could be applied to the conflict between scientific knowledge and students’ intuitive knowledge (Albanese & Vicentini, 1997). The first level concerns the relation between intuitive knowledge and the empirical laws of physics or chemistry, while the second level concerns the relation among the abstract entities in the scientific model and the primary scientific model.

The result of the questionnaire indicated that students had difficulties transferring the properties of the macroscopic word to the properties of the microscopic world. Albanese and Vicentini (1997) suggest that there are three aspects of the problem that need to be taken into consideration:

1. The passage from a continuous to a discrete conception of the structure of matter is crucial, and it is an important aspect of conceptual change from intuitive to scientific physics.
2. When using the particle model of matter, the model must be explained. The rules of how to use and interpret it must be clear, and the limitations should be exposed. A connection between physics and chemistry should be made, and it should be explained to students that the same model could show both physical and chemical properties.
3. The students are very flexible to new technology, and since they are used to computers, their mode of perception is visually oriented. It is important to know how visual transmission of knowledge works, to create conceptual links between the levels of description for effective learning.

5.3.1.3 Secondary Students’ Mental Models of Atoms and Molecules: Implications for Teaching Chemistry.

In everyday life, students interact with the world and create their own mental models of different phenomena (Harrison & Treagust, 1996). This prior knowledge directly influences what the student will learn in the classroom, and this will vary among all students in a single classroom. Some misconceptions are more common than others, and are therefore well documented. Mental models are not always correct, but they have to be functional if students are to be able to use them for reasoning and problem solving (Harrison & Treagust, 1996).

This article presents a descriptive study of students’ mental models of atoms and molecules. Harrison & Treagust (1996) describe a study where they investigated students’ perceptions of atoms and molecules. Forty-eight students in grade 8-10 participated in the study. The results showed that the most common mental models among students consisted of comparing the atom to a ball, a solar system, or a plum. In addition, students had difficulties understanding the teacher’s analogies for describing the shells or the clouds of electrons (Harrison & Treagust, 1996). In the study, six models of the atom were used: solar system model, orbits model, multiple orbits model, orbitals model, electron cloud model and ball model. The students were asked which models they preferred and which they disliked. Twenty-four students disliked the orbitals model, and the authors suggest that an explanation might be that the students are not familiar with the model. Twenty-one students approved of the solar system model, and sixteen approved of the electron cloud model. The solar system model is probably popular because it is concrete. The orbits and the electrons in the model seem material, which make them easier for the students to imagine (Harrison & Treagust, 1996). Students may approve of the electron cloud model since the teacher has spoken of it in class. However, twice as many students disliked the electron cloud model than those who disliked the solar system model.
Although most students were aware that atoms are very small, some of the students in the study by Harrison and Treagust (1996) thought that one could observe atoms through a microscope, and that scientists have seen single atoms and their constituents (Harrison & Treagust, 1996). The belief that scientists have seen atoms indicates that students sometimes erroneously interpret pictures of atomic models. It is therefore very important for the teacher to explain that the models only are analogies of atoms, and not real pictures of them (Harrison & Treagust, 1996).

Ten of the 48 students in the study believed that atoms were living things (Harrison & Treagust, 1996). One source of this alternative conception could be that these students have integrated their mental models of cells into their mental models of atoms, probably since they both share entities such as “nuclei”.

The study also showed misconceptions of the texture of atoms among students (Harrison & Treagust, 1996). One misconception was that the atoms of hard matter, e.g. metals, are “hard”, and that the atoms of soft matter, e.g. liquids, are “soft”. “Shell” also seems to be an expression that should be used with caution since students often interpret shells as being something hard that protects the atom from the outside world (Harrison & Treagust, 1996). Some students used the term “electron cloud” instead of shells, and they explained that the clouds are not solid (Harrison & Treagust, 1996). A further misconception was that students thought of an electron cloud as a cloud in the sky. They therefore believe that the electron cloud is like a matrix with electrons embedded in it, rather than believing that the cloud only consists of electrons (Harrison & Treagust, 1996). Both “shell” and “cloud” are words that are familiar to the students from everyday life, and they already have mental models to describe these words. Therefore, they must be carefully explained when used as metaphors in science education in explanation of atomic phenomena.

5.3.1.4 Why we should teach the Bohr model and how to teach it effectively.

Since the Bohr model of the atom does not represent the quantum nature of the electrons in atoms, some educators suggest that we should not teach it in school (McKagan, Perkins, & Wieman, 2008). This article presents results from a study where a curriculum for teaching the atom by using the Bohr and Schrödinger models was created. Various versions of the curriculum were used, and students’ descriptions of the atom were assessed in the final
exams. The authors concluded that students were more likely to use only the Bohr model to describe the atom if there was little connection between the Bohr and the Schrödinger model in the curriculum. If students were taught modelling skills for integrating between the models, they were more likely to use the Schrödinger model of the atom. It is important to discuss the differences and similarities between the models, which will make it easier for the students to adapt the Schrödinger model of the atom (McKagan, Perkins, & Wieman, 2008).

In this article, three historical models of the atom were used:

- The Bohr model of the atom: electrons are point charges that move in fixed orbits around the nucleus.
- The de Broglie model of the atom: the electrons are standing waves on rings around the nucleus. These rings have the same radii as the orbits in the Bohr model.
- The Schrödinger model of the atom: electrons are probability-clouds. By solving the 3-D Schrödinger equation for the Coulomb potential applied upon an electron from the nucleus, the density of the cloud is provided (McKagan, Perkins, & Wieman, 2008).

Some researchers think that the Bohr model is an inappropriate way of teaching the atom, since it does not communicate the quantum nature of the electrons (McKagan, Perkins, & Wieman, 2008). The Bohr model, however, could be a good start for teaching the atom to learn about particles and how the electrons move around the nucleus, and it is important to learn it as a representative of a historical step in scientific understanding about the atom. The Bohr model is also used at a scientific level for solving simple problems, and therefore the students should learn this useful tool as well.

According to the authors, studies have also shown that it is seldom successful to avoid discussing misconceptions. It is better to explicitly address the problems that are common among students (McKagan, Perkins, & Wieman, 2008).

The study described in this article was carried out to answer the question of whether the Bohr model could be an obstacle in learning the Schrödinger model (McKagan, Perkins, & Wieman, 2008). The authors transformed a modern physics course for engineering majors, and taught them for two semesters. Consequently, they were taught for two semesters by another professor using the same materials. The researchers wanted to investigate whether a
well-designed course that included the Bohr model could still assist in developing an understanding of the atom based on the Schrödinger model among students.

The development of the historical models of the atom was discussed during lectures (McKagan, Perkins, & Wieman, 2008). The authors focused a lot on model building and the reasoning behind the models. Limitations of a previous model were always discussed before moving on to the next model. Models were compared and contrasted, and the advantages and limitations of each model were discussed. The reasoning behind the Bohr and Schrödinger models was the main emphasis, rather than the mathematics behind them.

All four semesters was followed by an exam, and all of these exams contained one question that was always the same:

A Hydrogen atom is in its lowest energy state. Use words, graphs and diagrams to describe the structure of a Hydrogen atom in its lowest energy state (ground state). Include in your description:

- At least two ideas that are important to any accurate description of a hydrogen atom.
- An electron energy level diagram of this atom, including numerical values for the first few energy levels and indicating the level that the electron is in when it is in its ground state.
- A diagram illustrating how to accurately think about the distance of the electron from the nucleus for this atom (McKagan, Perkins, & Wieman, 2008, p. 3).

The answers to these questions shows how students think about atoms, and the third point where they are asked to reason about the distance of electrons to the nucleus forces them to choose between the Bohr or the Schrödinger model to analyse the differences between these models. The students were not asked to use any historic model to describe the atom. This was a deliberately chosen strategy by the authors, since if they asked for a model, the students would most likely choose the Schrödinger model even if they would not otherwise apply it (McKagan, Perkins, & Wieman, 2008).

When analysing students’ answers, the authors determined which models the students used to describe the atom. Many students used multiple models for describing the atom, so one student could use more than one model. The use of a model was noted even if they used it
implicitly, i.e. they described the properties of a model without naming the model. The goal of the authors was for all students to use the Schrödinger model since it was considered the most “correct” model, but other models did not necessary have to be excluded (McKagan, Perkins, & Wieman, 2008).

Based on the results of the exam in the first two semesters, nearly a quarter of the students used the Bohr model alone. However, a majority of the students used the Schrödinger model. In the exam following the first semester, there was an additional question about the angular quantum number, which prompted students to use the Schrödinger model. This question was removed in the exam following the second semester, and the percentage of students who used the Schrödinger equation to describe the atom decreased from 72% to 60% (McKagan, Perkins, & Wieman, 2008).

In the first semester, the students had difficulties relating the Schrödinger model to the other historical models of the atom. The reason for this could be that the authors spent a lot of time teaching the background knowledge that is necessary for understanding the Schrödinger model before teaching the model itself, which created a gap between this and previous models. In the following semesters, they focused more on relating the Schrödinger model back to the previous models, and the improvement upon using this model was discussed. Interactive simulations of Rutherford scattering and the different models of the hydrogen atom from PhET (Physics Education Technology) were also used. Following this, 76%-80% of the students used the Schrödinger model to answer the question, and only 13%-16% of the students used the Bohr model alone. This shows that the Bohr model does not have to be an obstacle for learning the Schrödinger model (McKagan, Perkins, & Wieman, 2008). When students had been taught about the connections between the models and the reasoning behind them, a larger percentage of students discussed the models explicitly.

The result of this study is that the Bohr model does not have to be an obstacle for learning the Schrödinger model of the atom (McKagan, Perkins, & Wieman, 2008). The authors of this study refer to two previous studies made in Germany and Greece, which yielded similar results. An aspect in common among these studies is that they all emphasize comparing and contrasting the Bohr model to other models of the atom. It seems to be important for the students to place the Bohr model in a context and be able to move beyond it in adaption of new models (McKagan, Perkins, & Wieman, 2008).
5.3.1.5 Identifying Atomic Structure as a Threshold Concept: Student mental models and troublesomeness.

The microscopic world of atoms is very abstract, and misconceptions among students are common (Park & Light, 2009). In the USA, grades 9-12 are considered a developmental phase in which students are able to make connections between the macroscopic and the microscopic world. Nevertheless, studies have highlighted difficulties and misconceptions about the particle nature of matter and atomic structure at these levels. This study explores the troublesome nature of learning atomic structure and attempts to better understand the conceptual barriers in this regard (Park & Light, 2009).

The participants of this study were 20 first-year college students in an introductory general chemistry class at an American Midwestern university. From this sample, three students participated in an in-depth analysis (Park & Light, 2009). The course focused mainly on atomic structure. All 20 students were interviewed before and after class, and different mental models of atomic structure were derived from the students’ answers. Questions were prepared to explore the conceptions of atomic structure among students. The answers obtained from the three students, who showed the most distinctive paths across the threshold of understanding, were analysed.

In this study, four models of the atom were used to label the students’ mental models: the particle model, the nuclear model, the Bohr model and the quantum model (Park & Light, 2009). The students’ answers were also analysed in terms of levels of understanding. The thirteen levels of understanding and the four atomic models were combined and used to classify the mental models among the students (Park & Light, 2009, p. 240). The answers were coded in terms of scientific models and by levels of understanding. Ten randomly selected interviews were also coded by another expert with a Masters if Science degree in physics, so as to improve the reliability of the study.

As mentioned earlier, the three students were chosen since they had distinctive pathways paths across the threshold of understanding. The first student was chosen since he used the Bohr model in both the pre- and post-interviews, even though he had gained new knowledge throughout the course. The second student was chosen since he possessed the most
sophisticated model to describe the atom. The third student was chosen since he used the Bohr model in the pre-interview, but attained a more sophisticated understanding throughout the course, and used a model more like the target model in the post-interviews (Park & Light, 2009). These three students each held a single coherent model of the atom. The other 17 students in the study created individual models consisting of fragments of multiple models.

This study showed that the Bohr model of the atom has a strong influence on students. Two of the three students in the study used this model to begin with. A change in understanding towards the quantum model of the atom depends on whether the student has understood the concepts of the probability of finding electrons and the quantization of energy, respectively (Park & Light, 2009). These two concepts are considered “key dimensions of the threshold concept of atomic structure” (Park & Light, 2009, pp. 251). The two students using the Bohr model did not understand the probability concept good enough to use the quantum model of the atom. The third student who used a more quantum-like model in the post-interview, showed an understanding of the wave properties of the electrons, but since he did not understand the probability concept, he created an individual model of his own and remained using the Bohr model (Park & Light, 2009). Energy quantization was another threshold barrier for the third student, which stopped him from moving beyond the Bohr model to the quantum model of the atom.

One of the conclusions of this study is that threshold concepts cannot be identified by the experience of experts, but need to be identified by the experience of students (Park & Light, 2009). Students need to be guided towards the target model in their own level of understanding.

5.3.1.6 Atomic Orbitals, Molecular Orbitals and Related Concepts: Conceptual Difficulties Among Chemistry Students.

This article describes a study that investigates students’ understanding of atomic orbitals, molecular orbitals and related concepts in an undergraduate quantum chemistry course (Tsaparlis, 1997). Orbitals are an abstract concept that is difficult for students to acquire, and some researchers even suggest that it should not be taught to students. Other researchers are of the opinion that it is wrong to teach historical models that are now scientifically defunct, and that students need to learn about orbitals.
For this study, data from final exams in a compulsory quantum chemistry course in the fourth year of university were used (Tsaparlis, 1997). The students had an elementary level of prior knowledge, on an elementary level, on atomic and molecular orbitals. The teaching method was traditional and consisted of lectures and formal teaching. The exam consisted of mostly free-response questions, with some multiple-choice questions. Six examination papers answered by different students were used for analysis in this study. This study was carried out during three years, and a total of 506 students took the final exam. Two hundred and twelve students passed the exam, and these successful students were included in this study.

One examination question asked the students to define an atomic orbital (Tsaparlis, 1997). Seventeen percent of the students did not answer this question at all, and among those who did answer it, the performance was low. Another question concerned the mathematical models of atomic orbitals, which also proved to be very difficult for the students. The performance on questions about the shape of atomic orbitals was also low, but when the university course started to include this kind of question in all exams, the performance improved. This does not necessarily imply meaningful learning, other than the students simply becoming aware that this was important.

The conclusion of this study is that it is difficult to change misconceptions among students (Tsaparlis, 1997). However, there are some techniques that can be used. One technique is to integrate different conceptions and to create links between them. Another is to differentiate between conceptions and try to identify and discuss differences between them.

The connections between mathematics and physics must also be emphasized, e.g. that the concepts derived from the Schrödinger equation is an approximation of nature (Tsaparlis, 1997).

The author suggests that further research must be done that can help increase the understanding of students’ misconceptions (Tsaparlis, 1997). If the teacher is aware of common incorrect mental models among students, the teacher can help the students to create more effective and meaningful models.
5.3.1.7 Examining Pre-Service Teachers’ Use of Atomic Models in Explaining Subsequent Ionisation Energy Values.

This article describes a study that investigates the atomic models that are used by pre-service teachers to teach ionization energy phenomena (Wheeldon, 2012). Thirty-one pre-service teachers participated in the study and were asked to describe and explain the Rutherford model, the Electron cloud micrograph model, the Bohr model and the Schrödinger model of the atom. They were also asked to explain the subsequent ionisation energy values for the oxygen atom.

Effective teachers should be able to select and evaluate models that provide links between observed phenomena in the macroscopic world and microscopic properties (Wheeldon, 2012). The ability to choose the most effective models can be problematic for two reasons. Firstly, it is difficult to understand the usefulness of more complex models. Secondly, there are three levels for observing phenomena that need to be reflected upon when selecting appropriate models for chemistry explanations: the macroscopic level, the microscopic level and the symbolic representational level (Wheeldon, 2012). An effective explanation should relate these levels to each other.

Semi-structured interviews were used for this study, with a standardised set of questions to enable comparability (Wheeldon, 2012). The questions used probed the following three areas of understanding:

- The teachers were asked to explain the ionisation energy values of an oxygen atom with the help of a graph as a representation of the phenomenon.
- The teachers were asked to explain different atomic models with pictures of the models used as a stimulus.
- The teachers were asked to explain what models would be useful for explaining and why they would be helpful.

Two interview sessions were held. In the first session, 16 chemistry specialist pre-service science teachers, seven biology specialists and one physics specialist participated. In the second interview, seven chemistry specialist pre-service secondary science teachers participated (Wheeldon, 2012). The answering rate of the interviews was 100%.
All 31 teachers considered the Bohr or Schrödinger models of the atom, or a combination of these model and others, most useful for explaining subsequent ionisation energies. (Wheeldon, 2012). Seven of the teachers thought that only the Bohr model was effective for explaining this phenomenon, and one teacher thought that only the Schrödinger model was effective. When explaining the energy levels, 14 of the teachers only used Rutherford/Bohr features of the atom. Sixteen of the teachers used both Rutherford/Bohr models and the Schrödinger model when explaining, and included use of the terms “shell” and “orbital” in their explanations. One teacher only thought that the Schrödinger model was helpful, and used terms such as “orbitals” and “probability” in his explanations.

The conclusions drawn by the author of this article are that teachers who use the Schrödinger model in their explanations, tended to use this to develop arguments about interactions between electrons. If the teachers did not use ideas about electrostatic repulsion, they tended to use the Bohr/Rutherford model, and drew a Bohr model with shells to demonstrate the distance effect on ionisation energies (Wheeldon, 2012). Since the electrostatic properties of nucleus and electrons are not provided by the Bohr model, so some teachers used hybrid models to explain this.

5.3.1.8 Conceptualizing quanta: Illuminating the ground state of student understanding of atomic orbitals.

In this article, Taber (2002) discusses student understanding of the orbital concept and related ideas. The data he presents was obtained from an in-depth research, with a small sample of students from the U.K.

During lower secondary school (11-14 years of age), students learn about the quantum theory of matter, which implies that matter consists of discrete particles, i.e. it is not continuous (Taber, 2002). This theory can also be referred to as the kinetic theory in physics, and the molecular model of matter in chemistry. This concept is often difficult for students to understand. In upper secondary school (14-16 years of age), students are taught about the atom, molecules and ions, and they are exposed to the term fundamental particles for referring to the electron, proton and neutron.
In lower secondary school, the word *particle* is simply used to describe the quanta of matter (Taber, 2002). This might be confusing for students, since the term is also used to refer to small components of macroscopic matter, such as dust particles and grains of sand, as particles (Taber, 2002). Taber (2002) suggests that the term *quanticles* could be used to describe atomic particles such as electrons, molecules and ions. Inappropriate labels are a major problem when learning and teaching science, which can lead to misunderstandings.

Since atoms and molecules cannot be seen with the naked eye, models are necessary in science education (Taber, 2002). It is common that textbooks display pictures derived from scanning tunnelling microscopes and it is common that students believe that these pictures are magnifications rather than produced images. Therefore it is important that the models, which are used in the learning process, are explicitly explained to the students.

To shift from the macroscopic to the microscopic world can be challenging for students (Taber, 2002). It is therefore important for teachers to be clear about which level of organisation they are referring to.

This article discusses the results from an interview-based study. The study was designed to explore the development of understanding of chemical bonds among fifteen college students (16-18 years of age) from the UK. The aim of the study was to describe students understanding of the atomic orbital concept and related ideas.

Taber (2002) summarizes the findings of the study in five points:

1. Students did not understand why quantization was introduced into the atomic model
2. Students had problems with forming atomic concepts
3. Students found concepts such as shells, orbitals and energy levels confusing
4. Students did not fully understand the concept of electronic spin
5. Students found the designation of orbitals confusing.

(Taber, 2002, p. 150)

Regarding the first point, the study showed that students accept the quantum model of the atom, but they may not understand why it is introduced (Taber, 2002). The students need to understand that the planetary model has flaws, and that the idea of the atom would collapse without the quantum theory.
Students in the study had problems with defining the term *orbital* correctly (Taber, 2002). Some students used the word *orbital* although their explanation seemed closer to the notion of *orbit*. Confusion between *shells* and *orbitals* was common. When new terms, such as *orbitals* and *energy levels* are presented to the students, they are expected to understand them. They are expected to understand that orbitals may be grouped into sub shells, and sub shells may be grouped into shells. However, these conceptual schemata, however, are difficult for students to master.

Representations of the atom might show electrons arranged in shells, orbitals or illustrate the density of electrons. It is difficult to draw a meaningful representation of a technically infinite orbital, and students may confuse the orbital itself and an illustration of overall electron density (Taber, Conceptualizing Quanta: Illuminating the Ground State of Student Understanding of Atomic Orbitals, 2002).

The concept of energy levels is also commonly confused with shells, sub-shells and orbitals (Taber, 2002). One of the student conceptions exposed in this study were that the shells or the orbitals represented the energy levels.

The author draws the conclusion that students may have difficulties constructing scientific models of the quantized atom in terms of orbitals and related concepts (Taber, 2002). In the beginning of the course, the students were familiar with the planetary model of the atom and the term *shells*. When they were introduced to quantum theory, and learned the new terms *quantum* and *orbital*, they simply relabelled their existing understanding, e.g. referring to the shells as *orbitals*. Students also had problems with distinguishing between concepts, e.g. orbitals and shells. Teachers need to scaffold the students’ learning and help them avoid cognitive overload when introducing new concepts and ideas.

**5.3.1.9 Atomic orbitals and their representation: Can 3-D computer graphics help conceptual understanding?**

When learning quantum mechanics, students have to use probabilistic notions, which they often find difficult (Trindade, Fiolhais, & Gil, 2005). It is often assumed that students master these concepts, and therefore teachers and textbooks fail to awaken interest among students.
A consequence of this is that students often have several misconceptions regarding quantum mechanical concepts.

The shapes and symmetry of orbitals can effectively be taught and studied with spatial visual representations (Trindade, Fiolhais, & Gil, 2005). Research has been conducted on students’ misconceptions of quantum concepts, but few attempts have been made to probe how visual representations can improve students’ understanding of the topic. One of the most effective and promising learning tools are virtual environments, which make the user believe that s/he is actually in the learning environment with the help of 3-D graphics.

This article presents a study with the aim to analyse the utility of virtual environment in science education. The method of the study was to create a 3-D virtual environment called Virtual water. It describes the microscopic structure of water, and it allows the user to explore phases and phase transitions, as well as atomic and molecular orbits (Trindade, Fiolhais, & Gil, 2005). It was shown that Virtual water has helped students to acquire a better understanding of the phases and the transitions between them.

Data was gathered from 20 first-year university students before and after the use of Virtual water. The authors uncovered three common misconceptions among students. Firstly, students often use the Bohr model to represent the atom, where electrons orbit the nucleus with fixed radii (Trindade, Fiolhais, & Gil, 2005). Secondly, they often have an incorrect understanding of charge, and have the incorrect conceptions related to repulsion and attraction between charges. Lastly, students often have the misconception that atoms have fixed shells in which electrons move.

In Virtual water, the students interacted with a 3-D simulation representing the atomic orbitals of hydrogen (Trindade, Fiolhais, & Gil, 2005). According to the authors, probability density of electrons is most effectively represented by dots. This is most effective when the image can be rotated, wherein the 3-D representation allows the viewer to fly through the orbital. The students can rotate the orbital, and for each orbital, the viewer can select different electron densities. The viewer is also able to view a “cross-section” of the orbital, to observe how it looks inside.
Before and after the use of the virtual reality simulation, the following question was asked to the students: “How do you conceive electrons in an atom?” (Trindade, Fiolhais, & Gil, 2005, s. 324). Before the use of Virtual water, one student used the planetary model to represent the atom, where electrons move around the nucleus in definite orbits. After the use of the simulation, he no longer believed that the electrons move in this classical way. A second student had the same conception as the first student before the use of the simulation, and after the use of the simulation he demonstrated the understanding that electrons have a probabilistic localization. However, the conceptions of all students did not improve, and some students thought that the orbitals were places in which the electrons are located, rather than that the orbitals represent the probabilistic location of the electrons.

A conclusion of the study was that students appreciated working with the virtual environment and they thought it was easier to understand the abstract nature of the atom when they were able to visualize it (Trindade, Fiolhais, & Gil, 2005).

5.3.1.10 The Chocolate Shop and Atomic Orbitals: A New Atomic Model Created by High School Students to Teach Elementary Students.

This article describes an atomic orbital model created by students for students, called The Chocolate Shop (Liguori, 2014).

The orbital theory is a challenging concept for students to understand at university level (Liguori, 2014). The more complicated quantum aspects are not presented in high school since it is too advanced for school students to understand. Two-dimensional diagrams or three-dimensional videos are currently used in school to teach atomic orbitals. Analogies are also popular for explaining orbital ideas, e.g. the Bohr solar system model of the atom. However, orbitals are difficult for students at high school level to understand, since they are mathematical solutions of different energetic wave functions.

Difficulties with understanding orbital concepts led a class into a project were they were to create a new and simple model of the atomic orbitals (Liguori, 2014). The main question of this project was “Could the atomic orbitals be introduced to a lower class, for example fifth-grade elementary students?” (Liguori, 2014, pp. 1742). The model should explain atomic
structure with special attention given to orbitals, energetic levels and electron displacement in the atom.

The result of the project was a model called *The Chocolate shop* (Liguori, 2014). The atom was represented by the whole shop, and the nucleus was represented by a child. The orbitals were represented by boxes, containing at most two pieces of chocolate, according to Pauli’s principle (two electrons in each orbital). The boxes were placed on different shelves, and each shelf corresponds to an energy level. The lowest shelf represents the lowest energy. On the first shelf, one box (representing the 1s orbital) is found. The boxes representing the s-orbitals are cuboid and correspond to the spherical symmetry of this orbital. The second shelf contains four boxes, one cube which represents the 2s orbital, and three parallelepipeds spatially oriented along the x-, y- and z-axis, representing the 2p_x, 2p_y and 2p_z orbitals. In the third shelf, nine boxes are placed: the cubical 3s box, the 3p_x-, 3p_y- and 3p_z-boxes, and five boxed representing 3d orbitals. The 3d-boxes are positioned so that the 3d_{xy}, 3d_{xz} and the 3d_{yz}-orbital are placed directly on the shelf, and the 3d_{x^2-y^2} and the 3d_{z^2}-orbital are placed above the previous ones. The sizes of the boxes represents the orbital energy, which increases analogously with the height of the shelves.

The chocolate shop model was tested in a fifth grade elementary class (Liguori, 2014). In the beginning of the lesson, an illustration of the chocolate shop model was shown to the students. After this, the students participated in a roleplay where they were divided into three groups: six protons, six neutrons and six electrons. The neutrons and protons were tied together to represent the nucleus, and the electrons moved randomly around the nucleus in pairs. The illustration of the chocolate shop model was shown again to the students, and they were asked to interpret it in relation to the role play. They were a bit disappointed that the boxed only contained, at the most, two pieces of chocolate, even when the boxes became bigger. Otherwise they understood the model well, and they enjoyed working with it. The students’ responded to a multiple choice test at the end of the lesson to verify the efficacy of the chocolate shop model, and 90% of the students achieved maximum scores and 10% answered half of the items correctly.

According to the author, the chocolate shop model has some limitations. The shapes of the orbitals can be misleading (Liguori, 2014). The cube form of the s-orbitals represented the symmetry of the spherical s-orbitals, and the parallelepiped shape of the p-orbitals was used to
be able to represent their spatial orientation. The d-orbitals, however, have no connections to the parallelepiped shape of the boxes. Orbitals and electrons are two entities that cannot be separated, since the orbitals are mathematically related to the probability of finding the electrons around the nucleus.

The advantages of the model is that it can be closely related to students’ everyday life, and that it only demands a basic model of understanding, which bodes well for use of the representation tool in primary school (Liguori, 2014).
6 Discussion

In this section, the results and methods of this study are discussed. The results are discussed by revisiting the research questions of this study. In addition, the methods used to locate and analyse the literature are discussed.

6.1 Discussion of obtained results

6.1.1 What models, representations and simulations are used to teach the atom and atomic concepts in the science classroom?

Analysis of the included articles revealed three types of representations used to represent atomic phenomena: two-dimensional static diagrams or pictures (e.g. pictures of the atom), three-dimensional videos or simulations (e.g. virtual reality simulations), and visual analogies (e.g. the Bohr planetary model of the atom). These different kinds of representations are also mentioned in the background section of this study. Harrison and Treagust (1996) describe analogical models as models that share information with the phenomenon that they describe, and they can represent one or several attributes of the target. Analogical models can be concrete, e.g. a scale model of an object, or more abstract, e.g. a scientific model of an atom. Some models can be used to teach more that one concept at a time, e.g. the periodic table (Harrison and Treagust, 2000a). Processes can also be described by models, e.g. formulae to describe chemical reactions, or simulations to describe different phenomena. Physical and chemical formulae and equations are other examples of analogical models.

Two-dimensional pictures of historical and scientific models of the atom are most common in textbooks and are often used by teachers to explain atomic concepts (Adbo & Taber, 2009). The pictures often show an atom with an oversized nucleus. It is also common that textbooks show colourful pictures of atoms derived from scanning tunnelling microscopy (Taber, 2002). The models used for teaching the atom in school are often derived from the Bohr model of the atom, but when teaching electrostatic interaction the Schrödinger model (fig.3) is also popular (Adbo & Taber, 2009; McKagan, Perkins, & Wieman, 2008; Wheeldon, 2012).
When teaching molecules, colourful pictures are sometimes used to distinguish between different kinds of atoms (Albanese & Vicentini, 1997). Ball-and-stick 3-D models are another common model for describing molecules where the balls represent the atoms and the sticks represent the bonds.

There are ways of representing the atom that also include students’ interaction with different representational components. For example, Liguori (2014) describes a representation created by students for students called *The chocolate shop*, which describes an environment familiar to students everyday life. The students also participated in a role-play to learn about the orbital concept of the atom. The constructivist theory emphasizes the active role of the learner in understanding information, and the role-play about the orbital concept allows the learners to participate actively in the learning process (Woolfolk, 2010). Trindade, Fiolhais and Gil (2005) present a virtual reality environment as a promising and effective learning tool for understanding the particle nature of matter. With the help of 3D-graphics, the virtual environment allows the learner to be “inside” the actual learning environment.

Systems of multiple representations (MERs) can be used to explain a phenomenon in more than one way, which may support students in their learning. Several models are available for describing the atom, e.g. the Bohr model, the de Broglie model and the Schrödinger model. Different models of the atom are described in the background of this study (see section 3.2.6.1.)

### 6.1.2 How do learners interpret different representations of the atom, and what mental models do student construct and use to understand the atom?

A majority of the articles found in this study focus on revealing students’ alternative conceptions of the atom, rather than their correct conceptions. The misconceptions, however, are interesting and important for science teachers to have in mind when introducing students to abstract and demanding concepts. According to Adbo and Taber (2009), students often interpret models as correct representations of reality, especially if they are not explicitly taught about the limitations of the model. This result is also described in the background, but according to Harrison and Treagust (2000a) students can learn to use multiple representations to describe a phenomenon, and as a consequence they discover that no model is completely correct. Several studies show that the transition and connection between microscopic and
macroscopic matter is difficult for students to understand. Students might interpret scientific concepts incorrectly since the same word already has a meaning in their everyday life. For example, the term *particle* can be difficult for students. When a teacher talks of particles in a microscopic context, students may apply the same properties to particles in the macroscopic world. Students can interpret a particle as a grain of sand or a speck of dust, while the teacher means quanta of matter. This can be compared to the background of this study and the cognitive-affective theory described by Moreno and Mayer (2007). According to this theory humans have different modality channels for interpreting information, and only a limited amount of information can be processed at one time. Learning becomes meaningful when the learner consciously selects and organizes information and integrates it with existing knowledge. Learners’ prior knowledge will affect their attention and perception, and their mental models will therefore depend on their already existing knowledge. Learning becomes meaningful when the learner consciously selects and organizes information and integrates it with existing knowledge. The study by Harrison and Treagust (1996) showed that some students confused the atom with a cell, probably since both cells and atoms have nuclei, and believed that atoms are living entities. They also tended to believe that atoms of hard matter are hard, and that the atoms of soft matter are soft. This is another example of students’ difficulties with relating the microscopic and macroscopic world.

A common conception among students is that the nucleus is like a ball, containing proton and neutrons. They believe that electrons orbit the nucleus, like planets around the sun, but that the nucleus itself remains static. Even though it is common to use 2-D pictures of the atom when teaching, students do not seem to have difficulties with visualizing the atom as a spherical shape. However, a problem with the pictures seems to be the oversized nucleus in comparison with the atom as a whole, which is common in textbooks. Although there is this shortfall, the study by Adbo and Taber (2009) revealed one student who mentioned that the distances between the nucleus and the electrons are actually far greater.

The results of this systematic literature review indicate that students seem to be familiar with the subatomic particles of the atom, and they know that the nucleus is neutral. In the study by Adbo and Taber (2009), most students agreed that the neutral charge of the nucleus is a result of that the charges of the electrons and protons cancel each other out. When comparing this to the background of this systematic literature review, some differences are apparent. According to Taber (2003) students may believe that the neutrons in the nucleus neutralize the charge of
the protons. They focus more on a neutralizing process that the neutrons exert on the protons, rather than that the neutrons have a neutral charge. Taber also highlights students’ difficulties with understanding particulate ideas, which may lead to confusion assigned to the use of labels and terms. In addition, even if they are aware of the subatomic particles, they sometimes find it difficult to understand how they interact.

The size of an atom can be confusing for students. Many students in the study by Harrison and Treagust (1996) believed that you could see individual atoms through a microscope. The reason for this might be the colourful pictures of atoms derived from scanning tunnelling microscopes for example, which are common in textbooks. Another conception students might develop as a consequence of these colourful pictures is that atoms have colour. The study by Albanese and Vincentini (1997) showed that 80% of 30 students believed that atoms had colour, and that the colour corresponded to the matter at the macroscopic level that the atom constituted.

The results also revealed the orbital concept to be confusing for students. The study by Harrison and Treagust (1996) showed that many students disliked the orbital model of the atom, since it was unfamiliar to them. The solar system model (fig.2) was very popular, probably since it is concrete and easier to understand. Some students also approved of the electron cloud model, and the reason for that was probably that the teacher had spoken of it in class. It is common that students use the notions shell and orbital synonymously. Students are first introduced to the Bohr model of the atom, and learn about the subatomic particles and the shells. When they are introduced to the quantum model of the atom, with the new terms orbital and quantum, they may simply re-label their existing understanding, e.g. refer to the shells as orbitals (Taber, 2002). The term electron cloud can also be confusing for students (Harrison & Treagust, 1996). They are familiar with the word cloud from their everyday life, and they may therefore assimilate the new concept electron cloud into their already excising conceptual schemes about clouds, and formulate the mental model that the electron cloud is like a matrix with electrons embedded in it.

Several of the articles mention that the Bohr model of the atom has a strong influence on students’ conceptual understanding of the atom. In the study by Park and Light (2009), the authors investigate how students’ conceptions of the atom changed during a chemistry course. A conclusion was that understanding the concepts of probability and quantization of energy...
was necessary for the students to change and develop their conceptual understanding from the Bohr model to the quantum model of the atom. Otherwise, they will not adjust their mental model beyond that of the Bohr model of the atom. If they understand the wave properties of the electrons, they may create an individual hybrid model of their own, but if they do not also understand energy quantization, they will probably not be able to use the Schrödinger model (fig.3) to describe the atom. In a certain respect, it seems that the Bohr model could actually be an obstacle for learning the true quantum nature of the atom. However, McKagan, Perkins and Wieman (2008) drew the conclusion that students can move beyond the Bohr model, if the teacher explicitly compares and contrasts the Bohr model to other models of the atom.

6.1.3 How can the representations be used and designed for meaningful learning and teaching of the atom and atomic concepts?

Several of the studies analysed in this review show that students have difficulties relating between the microscopic and the macroscopic world (Adbo & Taber, 2009; Albanese & Vicentini, 1997; Park & Light, 2009; Wheeldon, 2012; Taber, 2002). It is therefore important that teachers clarify what level of organisation they are referring to when presenting a model (Taber, 2002). Explanations that link between the microscopic world, the macroscopic world and scientific models are effective for improving students’ understanding (Wheeldon, 2012).

Some of the articles highlight the importance of explaining the rules of the models before using them to explain atom-related concepts. The limitations and advantages of the representations should also be discussed (Albanese & Vicentini, 1997). If the limitations of the models are not communicated to the students, they might perceive the models as correct representations of reality, which might lead to alternative conceptions (Adbo & Taber, 2009). Albanese and Vincentini (1997) also suggest that teachers should emphasize the relation between chemistry and physics when teaching the particle nature of matter, and explain that the same model could be used to demonstrate both chemical and physical properties. From a constructivist point of view, it is important that the models and representations used can be meaningfully related to students’ prior knowledge. This can be done using appropriate analogies and metaphors, which allow the students to make sense of information in a context that they are already familiar with (Woolfolk, 2010).
Multiple representations can be used to explain a phenomenon in more than one way, which may support students in their learning. Different types of models can be used for describing different phenomena, and they may be effective or not depending on what content the teacher aims to teach. Another benefit of working with systems of different representations is that students have the opportunity to choose the representation that they prefer (Ainsworth, 1999). When using systems of multiple external representations (MERs), it is important to explain to the students how the models function together, and what each respective model conveys that the other does not. The Bohr model of the atom is a good way of teaching subatomic particles and for demonstrating that the atom has a nucleus consisting of protons and neutrons, with electrons orbiting it. However, the Bohr model does not exhibit the quantum nature of matter, and therefore, some researchers are of the view that it should not be introduced in school (McKagan, Perkins, & Wieman, 2008). The study by McKagan, Perkins and Wieman (2009) show that the Bohr model does not have to be an obstacle for learning the Schrödinger model. The Schrödinger model is a more scientifically correct model, but it is more abstract and difficult for students to understand. McKagan, Perkins and Wieman (2009) drew the conclusion that students were more likely to only use the Bohr model to describe the atom if there was little connection between the Bohr and the Schrödinger model in the curriculum. If the students were taught modelling skills and how to integrate between the models, they were more likely to use the Schrödinger model of the atom. It is important to discuss the differences and similarities between the models, which will make it easier for the students to adapt the Schrödinger model of the atom. Comparing and contrasting models will hopefully make it easier for the students to understand why new models have been developed, and how to integrate the new information into their already excising conceptual schemes. Tsaparlis (1997) also emphasizes the importance of linking between different representations, as well as comparing and contrasting models to help change students incorrect alternative conceptions. The study by Wheeldon (2012) showed that pre-service teachers often used the Bohr/Rutherford model for explaining orbitals and shells, while the Schrödinger model was often used for explaining orbitals and probability. Teachers who use the Schrödinger model in their explanations, tended to use it to develop arguments about interactions between electrons, but if the teachers did not use ideas about electrostatic repulsion, they tended to use the Bohr/Rutherford model.

An important aspect that needs to be taken into consideration when designing systems of multiple representations is how support should be provided to help students translate between
the representations. Translating between representations in MERs is often demanding for learners, and implicit cues in representations can help support the translation process. For example, the same colours can be used to represent the same object in different representations, which can help students see connections between the representations more explicitly. Dynamic linking can support translation, e.g. a computer makes the translation. The learner can change something in one representation, and then see the results of his or her actions in another representation. The ability to make transformations between different representations is called “representational competence”, and novices in physics find it difficult to make these transformations (Kozma & Russel, 1997). Other aspects that need to be taken into consideration when designing MERs is the number of representations, how the information should be distributed between them, what form the representational system should have and in what sequence the representations should be presented (Ainsworth, 2006).

The use of simulations and interactive learning environments seem to have a positive effect on students’ learning. In the work performed by Trindade, Fiolhais and Gil (2005), the result showed that students appreciated the use of virtual reality simulations, since it made abstract concepts easier to understand when they could be visualized. The representations are most effective if they are simple and concrete, and since students learn in uniquely different ways, representations must be chosen with the learner and the situation taken into consideration (Ainsworth, 2006).

6.2 Discussion of methods used to locate and analyse the literature

When performing a systematic literature review, all research that has been done in response to the questions raised by the study, should be located and synthesized (Forsberg & Wengström, 2008). When searching for articles in the present study, some limiters were used, such as only consulting peer-reviewed literature published after 1990-01-01. For this study, one aim was to find recently conducted research, but since it was difficult to find literature about representations of the atom, the year 1990 was used as a limiter. Perhaps there are some interesting articles that were published earlier that could have been suitable for this study.

When searching for articles, different combinations of search terms were used. Perhaps, by combining them in different ways, the databases could have returned other interesting articles,
which were not included in this study. Although, the Google scholar database was used to cover articles that were not returned during search in ERIC and Scopus.

For this study, the databases ERIC and Scopus were used for running the search strings. In addition, Google scholar was used to find articles located in references to other articles returned during search in ERIC and Scopus. Google scholar was also used to run search strings, but since this database only offers a narrow supply of search limiters, the number of “hits” became too large to manage. Google Scholar did return a lot of promising articles, so as a consequence of the difficulty of narrowing down the results, some interesting articles were probably missed if those respective journal sources were not listed in the ERIC or Scopus databases.

Many of the articles that were synthesized in the findings leaned more towards chemistry than physics. Upon analysis, the atom is a concept used in both physics and chemistry, and more research has been done in the chemistry field about students’ conceptions of the atom. Therefore, articles about chemistry were also included.

6.3 Evaluation of the quality of the articles included for analysis

In this study, the quality of the articles included for analysis was evaluated, based on the criteria presented in the method section (4.3) of this study. The results are presented in table 13 below. If the articles correspond well to questions 1 and 3, the measuring method measures what is aimed to measure and the validity can be deemed high. If the articles correspond well to question 2, the number of participants is high enough for the research method to be reliable, if the intention of the method is to be generalizable.

In this section the method for analysing the quality of the articles is discussed. As a complement to table 13, the articles will also be discussed individually in terms of quality.

| Table 13: Evaluation of validity and reliability of the articles in the result. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Learners’ Mental Models        | Clear aim and well              | Semi-structured interviews.     | Interviews were used as a       |

58
<table>
<thead>
<tr>
<th>Study Title</th>
<th>Aim Formulation</th>
<th>Number of Participants</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why Do We Believe that an Atom is Colourless?</td>
<td>The aim of this study is to verify another previously made study. It is difficult to find well-formulated aims and questions in the text.</td>
<td>30 respondents to a questionnaire. Potentially low reliability.</td>
<td></td>
</tr>
<tr>
<td>Reflections about the Teaching of the Particle Model.</td>
<td>Well-formulated aim and questions.</td>
<td>Interviews with 48 participants should give a quite a high level of reliability.</td>
<td></td>
</tr>
<tr>
<td>Secondary Students’ Mental Models of Atoms and Molecules: Implications for Teaching Chemistry.</td>
<td>Well-formulated research question.</td>
<td>Four groups of students, with 189, 184, 94 and 153 students. This gives the result a high level of reliability.</td>
<td></td>
</tr>
<tr>
<td>Why we should teach the Bohr model and how to teach it effectively.</td>
<td>There is an aim of the study, but there are no well-formulated questions.</td>
<td>Three students were selected for interviews, from a sample of 20 students, based on test-results from tests before and after a lesson. Even if the method was interview-based, only three participants give a low reliability.</td>
<td></td>
</tr>
<tr>
<td>Identifying Atomic Structure as a Threshold Concept: Student mental models and troublesomeness.</td>
<td>Well-formulated questions and aim.</td>
<td>Covers a period of three years and a total of 212 participants, restricted to successful students. This gives a high level of reliability.</td>
<td></td>
</tr>
</tbody>
</table>
| Atomic Orbitals, Molecular Orbitals and Related Concepts: Conceptual Difficulties Among Chemistry Students. |                        | Data from final-examinations were used for this research. Responds well to the questions of the study.  

59
### Examining Pre-Service Teachers’ Use of Atomic Models in Explaining Subsequent Ionisation Energy Values.

**Clear aim and well-formulated question.**

Two samples of participants, with 16 and 7 pre-service teachers respectively.

Semi-structured interviews, with a standardized set of questions to provide comparability. Good validity.

<table>
<thead>
<tr>
<th>Conceptualizing quanta: Illumination the ground state of student understanding of atomic orbitals.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear aim and well-formulated questions.</td>
</tr>
<tr>
<td>Fifteen participants in the study, but since the method was interviews, the study might still deliver a high reliability.</td>
</tr>
<tr>
<td>In-depth interviews give a good view of how the students reason.</td>
</tr>
</tbody>
</table>

### Atomic orbitals and their representation: Can 3-D computer graphics help conceptual understanding?

**The study has a formulated question and a clear aim, but it was a bit difficult to find in the text.**

No subsection called “aim and purposes” for example.

Twenty participants. Both a written questionnaire and interviews were used.

Regarding the questionnaire, the reliability is low, but when using interviews, 20 participants can give a higher reliability.

| Good to use both a questionnaire and interviews. |

<table>
<thead>
<tr>
<th>Atomic orbitals and their representation: Can 3-D computer graphics help conceptual understanding?</th>
</tr>
</thead>
<tbody>
<tr>
<td>The study has a formulated question and a clear aim, but it was a bit difficult to find in the text.</td>
</tr>
<tr>
<td>No subsection called “aim and purposes” for example.</td>
</tr>
</tbody>
</table>

### The Chocolate Shop and Atomic Orbitals: A New Atomic Model Created by High School Students to Teach Elementary Students.

**Clear aim and well-formulated question.**

Eighteen students participated in the research. They got to try a new orbital model, and participate in a role-play. They took a multiple-choice test in the end of the lesson. The reliability is not very high, since the result cannot be generalised for all students.

The students got to test a new model and then answer a multiple-choice test. The measurement method tested what was aimed to be tested, so the validity of this study is good.

| The students got to test a new model and then answer a multiple-choice test. The measurement method tested what was aimed to be tested, so the validity of this study is good. |

---

To be able to generalise the findings of the study, the articles included for analysis should have high validity and reliability. Large sample sizes may help to improve the reliability of a study, since there are many data points to ascertain whether similar outcomes are being delivered. Nevertheless, a study with a small sample size can still give good and interesting results if the appropriate research method is used. For example, to be able to generalise the findings based on the answers of a questionnaire, the sample size should be quite large. However, if in-depth research methods, such as interviews, are used, even a small sample size...
can return results that could be generalizable. The answers from individual students can lead to interesting and valuable findings.

The study by Adbo and Taber (2009) was undertaken in Swedish secondary school, and the results might not be generalised for students in other countries. Different teaching environments and syllabi will affect the learning, and studies from international contexts would therefore be interesting to get a more generalizable picture of students understanding. The study was based on semi-structured interviews and participation in the interviews was voluntary. The fact that only volunteers participated might give a higher validity of the answers, since the students who wanted to participate probably find the study interesting and will give serious answers. The study was undertaken in two schools in two different municipalities, and since the results did not differ much between the schools, the authors suggest that the results could be applicable for other Swedish students at this age. However, the reliability of the study would be higher if the research was undertaken in more than two schools in different parts of the country, and perhaps even in international schools. The results might not be generalizable for students in other parts of the country for example, since different teachers teach their students in different ways. The authors of this study mention that in depth analysis should be used in combination with surveys of larger numbers to estimate how common the conceptions are in wider populations. A total of 18 interviews were conducted during the study. Since the research method was interviews, even small sample sizes can give generalizable results. The quality of this article can probably be deemed quite high since the authors have undertaken previous research in the field.

The study by Albanese and Vincentini (1997) was made to verify a previously made study, and 30 Italian students were interviewed with questions from a questionnaire. It is not clearly formulated if the 30 students were from the same school, and this might affect the generalizability of the results. Students who are taught by the same teacher will probably give similar answers, and it would therefore be interesting to have a sample of students from different schools to investigate if there are common conceptions among students undependable of the teaching environment.

Harrison and Treagust (1996) interviewed 48 students from three different schools, which improves the generalizability compared to a study undertaken at only one school. Interviews with probing questions were used to help students express their knowledge and
understanding. Participation in this study was voluntary, which might improve the validity of the findings. However, there might be a risk that only high-achieving students volunteer, and low-achieving students might therefore not be represented in the sample. The research method employed interviews, which might give a high reliability, especially since the sample size is quite large. The authors have conducted previous research in the field, and the quality of the article can therefore be deemed quite high.

The study conducted by McKagan, Perkins and Wieman (2008) is based on one simple and clear research question, and the authors state that the ideal study would be to compare student conceptions of atoms in two different courses. The research samples consisted of 189, 184, 94 and 153 students respectively. The aim of the study was to show if the Bohr model does not have to be an obstacle for learning the Schrödinger model of the atom. To prove this, these samples of students seem to be enough. The authors refer to two previous studies with similar results, conducted in Greece and in Germany. This implies that the results can be generalizable. The authors have conducted other research in the field, and the quality of the article can be deemed quite high.

Park and Light (2009) refers to previous studies by well-known authors in the same research area as their own. The connection between this study and previously made research supports why the aim and question of their study is relevant, and shows that the authors are well informed about what has been done in the field. Interviews were used as the research method, and the sample consisted of three students drawn from a sample of 20 students. Even if interviews can provide a generalizable results even with small sample sizes, three students are perhaps a bit too few. Twenty students answered pre-tests and post-tests and the three students who had the most distinctive paths were chosen for interviews. The authors themselves also suggest that further studies with larger sample sizes will provide richer information. Many of the references in this study can be recognised from other studies, which supports a high quality.

In the study by Tsaparlis (1997), final examination data were analysed. The author taught the course, posed the questions and analysed the answers, which might be both good and bad in terms of assigning the level of reliability of the results. The fact that the author has control over the entire learning process can be a benefit, but on the other hand, the analysis might be biased. The paper covers a period of three years, which can improve the reliability of the
result if the aim is for the results to be generalizable. This work was purely diagnostic, and the author suggests that further research is needed to understand the reasons behind students’ misconceptions and difficulties.

In the study by Wheeldon (2012), semi structured interviews were used as research method. A standardised set of questions was used for the interviews to allow comparability, which improves the quality of the results. The aim was to ask the participants for multimodal representations in their ideas, since asking for one specific model previously have shown to result in stereotypic images. The author states that this multimodal approach may provide additional reliability in considering the models that are expressed. The pre service teachers in the sample volunteered to participate, which may improve the quality of the results. The interviews were audio recorded to avoid the distraction of a camera, but notes were taken to record body language such as gestures to express models. The author discussed the limitations of the study, e.g. that the interviewed teachers might answer what the interviewer wants to hear, and that the answers are snap shots, which cannot be representative of the teachers’ general thinking. The author refers to several studies by well-known authors in the field, and the quality of the article can be deemed quite high.

In the study by Taber (2002) the sample consisted of 15 students from the UK, and interviews were used as research method. The author both taught the course and interviewed the students, so he was well familiar to the students. The students who participated in the interviews volunteered, which can improve the quality of their answers. The research was conducted with a small sample of students at a single university, so the results of the study cannot be generalised for all students at this level. This is also commented in the article by the author. He suggests that the results can be illustrative of types of thinking, but it cannot necessarily be representative for all students. A reader of this article must transfer the results to his or her own learning context. The author has produced more research in the field, and refers to other well-known researchers in this article, which allow the quality of this article to be deemed high.

Trindade, Fiolhais and Gil(2005) used a sample of 20 participants in their research about virtual environments. As a research method, both a written questionnaire and interviews were used. Regarding the questionnaire, the reliability based on the number of participants is low, but when using interviews, 20 participants can give a higher reliability. The aim and purposes
of the article are clear but difficult to locate in the text. The authors mention that this study is purely descriptive, and a method for evaluating the impact of learning more effectively is needed to be able to generalise the results.

Lastly, the article by Liguori (2014) describes a model for teaching atomic orbitals and how it was used in class. No generalizable results are provided, but it is an example of how models that link to students’ prior knowledge can be used to teach the atom and atomic concepts. The study is purely descriptive.

### 6.4 Conclusions

The abstract microscopic world of atoms cannot be seen with the naked eye, and models are therefore necessary and crucial educational tools for teaching atomic concepts in school. However, when using a model, it is important for the teacher to explain the rules of the model, and the advantages and limitations must be discussed. Otherwise, the students might interpret the models incorrectly. Todays’ students are very familiar with working with computers, and it is important that the simulations used in school are well designed. Simulations and virtual environments allow the student to explore the different atomic phenomena, which make the abstract concepts easier to visualize. In addition, students often enjoy working with these kinds of models, and it might motivate them in their learning process.

Students often find concepts of atomic structure difficult and confusing. The results in this study revealed the orbital concept to be confusing for students. The study by Harrison and Treagust (1996) showed that many students disliked the orbital model of the atom, since it was unfamiliar to them. The solar system model was very popular, probably since it is concrete and easier to understand. Alternative conceptions about atomic concepts are common among students, and it is important that teachers have students’ prior knowledge in mind when introducing new material. According to constructivist theory, it is most important that students have some knowledge to develop, even if this knowledge is not necessary scientifically correct.
Multiple representations can be used to explain a phenomenon in more than one way, which may support students in their learning. For example, when using different historic models of the atom, it is important to compare and contrast the models to each other, so that the students can place the models in a context. That will hopefully make it easier for the students to understand why new models have been developed, and how to integrate the new information into their already excising conceptual schemes. For example, the Bohr model has a strong influence on students’ conceptual understanding of the atom, according to the findings in several of the articles included for analysis. In a certain respect, it seems that the Bohr model could actually be an obstacle for learning the true quantum nature of the atom, but if the teacher explicitly compares and contrasts the Bohr model to other models of the atom, students can move beyond the Bohr model when creating their individual conceptions.

An important aspect that needs to be taken into consideration when designing systems of multiple representations is how support should be provided to help students translate between the representations. Translation is often demanding for learners, but the translation process can be supported by including different kinds of implicit cues in the representations. For example, the same colours can be used to represent the same object in different representations, which can help students see the connections between the representations more explicitly. Another example is to let a computer make the translation (dynamic-linking), where the learner can change something in one representation, and then see the results of his or her actions in another representation. The representations are most effective if they are simple and concrete, and since students are unique individuals who learn in different ways, representations must be chosen with the learner and the situation taken into consideration.

6.5 Implications for further research

Atomic concepts and orbital ideas are difficult for students to understand, and alternative conceptions are common. Several of the articles presented in the results discussed that the quantum model of the atom, e.g. the Schrödinger model, is difficult for students, especially since they have been taught the Bohr model earlier in school. It would be interesting if more research was conducted on how models can be best designed for teaching the quantum nature of the atom. Simulations are effective tools for teaching which students enjoy using, so
research about how effective simulations and virtual reality environments are best designed would also be a viable area for further research on students’ understanding of the atom.

The influence of one model on another when students learn about the atom would also be an interesting topic of research. It would be interesting to investigate what each model “offers” students’ interpretation processes, and how the students use the different representational features in each model to develop their understanding of the atom.
7 References


http://global.britannica.com/EBchecked/topic/528977/scientific-visualization


http://www.ne.se.e.bibl.liu.se/uppslagsverk/encyklopedi/lång/representation


### 7.1 Acknowledgement of sources for figures

All the images used in this document are creative commons and were retrieved from Wikimedia Commons, [http://commons.wikimedia.org](http://commons.wikimedia.org).


Plum pudding atom (Figure 1). Retrieved December 10, 2014 from Wikimedia Commons: [http://commons.wikimedia.org/wiki/File:Plum_pudding_atom.svg?uselang=sv](http://commons.wikimedia.org/wiki/File:Plum_pudding_atom.svg?uselang=sv)

Rutherford model of the atom (Figure 2). Retrieved December 10, 2014 from Wikimedia Commons: [http://commons.wikimedia.org/wiki/File:Rutherford_atom.svg](http://commons.wikimedia.org/wiki/File:Rutherford_atom.svg)