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## Teaching Quantum Mechanics Using qCraft

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*Author:*

Michaël Christiaan VAN DEN ENK  
[s1004654]

*Supervisors:*

Dr. H. H. LEEMKUIL  
Dr. H. VAN DER MEIJ

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# Abstract

This document describes the development of an instruction intended for teaching quantum mechanics to Dutch physics students within upper secondary education, which is necessary because of the implementation of quantum mechanics within the Centraal Eindexamen. This description entails a description of the development process, the design choices and the argumentations thereof and the evaluation approach and the results following from this evaluation. The instruction makes use of several instructional theories, suggestions from studied literature on the topic of quantum mechanics education and the results from the aforementioned evaluation. Furthermore, it is delivered by the medium of qCraft, which is a modification available for the game Minecraft, and therefore the instruction is delivered by game-based learning. Finally, it is intended as a purely conceptual instruction, instead of being experiment oriented or mathematically oriented. The instruction therefore serves as a pretraining for teaching various concepts within quantum mechanics, which can be followed by instruction about experiments conducted within the field of quantum mechanics and finally by instructions about the mathematics behind quantum mechanics. The evaluation is conducted by using qualitative research methods, which resulted in a display of different aspects of the instruction.

# Introduction

# Background

In the Netherlands, quantum mechanics always used to be a topic which schools themselves could choose to teach or not to teach. The only skill students had to know for the Centraal Eindexamen (the national central exams at the end of high school) which comes close to quantum mechanics is to elucidate the photoelectric effect and the wave-particle duality, mentioned within point 20 under subdomain E3 (Laan, 2013). However, one of the changes in the Centraal Eindexamen of 2016 was the addition of domain F1, which is called Quantum world (Groenen et al., 2014). For this subdomain the candidate has to be able to apply the wave-particle duality and the uncertainty principle of Heisenberg, and to explain the quantisation of energy levels in some examples with a simple quantum physical model. In order to give all candidates a chance of passing this subdomain, schools have to alter their programs in order to meet the expectations of the Centraal Eindexamen.

However, when searching the internet using the search machine Google concerning the implementation of quantum mechanics in Dutch high schools, the quantity and the quality of the results are very low. There are also no results to be found in the Dutch papers. An example is the Dutch site <http://www.quantumuniverse.nl/>, where teachers can find a small amount of brief courses on fundamental quantum mechanics, and where the forums only have 5 discussions, of which 4 are just started threads from the site administrator.

Upon finding this information, an expert was consulted to confirm this conjecture. The expert was researching the implementation of quantum mechanics on middle schools, and she also a first degree physics teacher. She stated that within her school there were no initiatives to bring this topic in their classrooms, and that their school was no exception as well.

The fact that next year domain F1 has to be fully implemented and taught to all vwo students who chose physics as an examination subject is therefore slowly turning into a sword of Damocles. This stresses the urgency for the development of new course material.

# Content

Quantum mechanics is not the easiest topic to introduce into physics education. The subject is very counterintuitive, and still poses headaches to many physicists today. The great physicist Richard Feynman is known for saying: “I think I can safely say that nobody understands quantum mechanics” (1965), and this statement still holds. Quantum mechanics is this counterintuitive because it contradicts a lot of axioms we inherited from classical physics. These contradictions are highlighted by an article written by Einstein, Podolsky, and Rosen (1935), which states that the current understanding of quantum mechanics contradict the criterion of reality and the hypothesis of locality.

There are a lot of resources available for teaching quantum mechanics. Most of these resources are academical and focus on teaching the mathematics. Their philosophy is that the student can only really get a grasp on quantum mechanics if he understand the underlying mathematical mechanics. An example of such a resource is Griffiths (2005). These resources are not very useful when teaching middle school students, because it demands an understanding of mathematics which is beyond the knowledge of middle school students, for example the integration of Schröder equations.

The other way of teaching quantum mechanics is by teaching the key principles of quantum mechanics. A fashion in which this could be achieved is by only considering the perfectly correlating instances. An example of such an instance is quantum teleportation. Zeilinger (2005) explains this phenomenon without having to resort to very complex mathematics, but still explaining the fundamentals of quantum mechanics, such as observer dependency, superposition and quantum entanglement. The instruction will therefore use quantum teleportation to explain these three fundamental principles, so the learner will gain a conceptual understanding of quantum mechanics.

One way of making principles more accessible for the learner is by using an educational game (Wouters & van Oostendorp, 2012). By using games, the content can be visualised, the learner can interact with the content and the content can be structured according to instructional theories. One game which exists to explain the fundamental principles of quantum mechanics is the modification qCraft for the game Minecraft. There are already resources which use qCraft to explain quantum mechanics, developed by the qCraft team. However, they lack use of educational resources like Smith and Ragan (2005). The resources also depend on different external resources, which makes it very complex and causes a lack of structure. Finally, it could make more use of the possibilities within Minecraft, like books presented in the game. Therefore, a new instruction will make an effort to replace these resources with a higher educational value for Dutch middle school students by analysis, using instructional theories and using the recommendations provided by the studied literature. This literature study is included in a separate document.

# Development approach

As a general outline of the development process, the generic model is used (Plomp, Feteris, & Pieters, 1992) (see figure 1). This model provides a framework for the process of instruction development, containing the phases analysis, design, development, implementation and evaluation. As can be seen, implementation and evaluation have to be conducted throughout the development process. Because of time constraints of this project, the development of the instruction will go only as far as developing the instruction, leaving the implementation and final evaluation to further research.

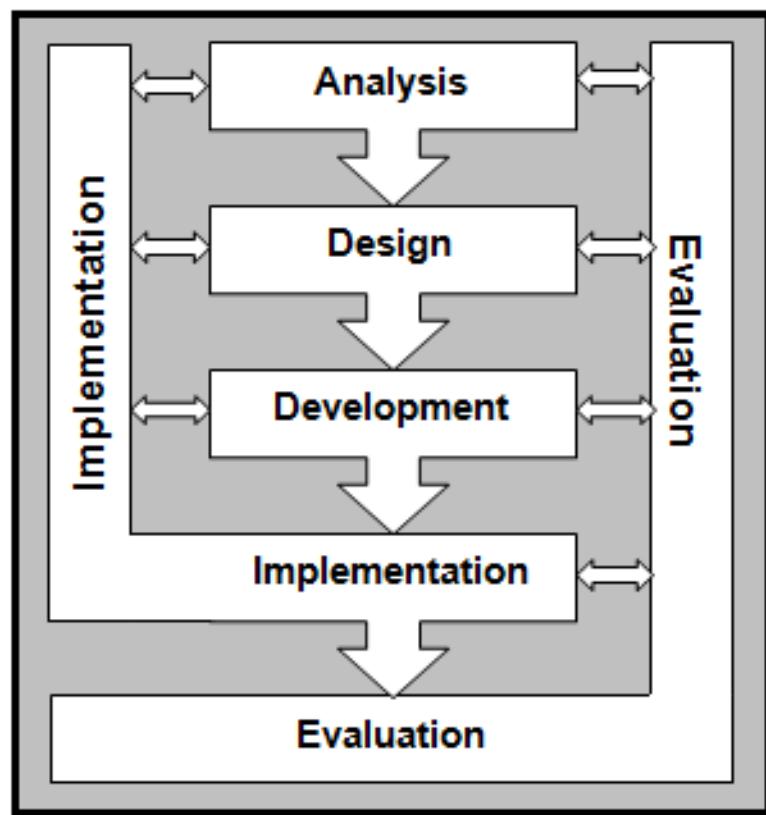


Figure 1: The generic model by Plomp et al. (1992)

# Analyses

The first step of the Generic Model by Plomp et al. (1992) (see figure 1 on page 10) is Analysis. Smith and Ragan (2005) give an elaborated description of how to perform these analyses for instructional design. They distinguish three different kinds of analysis: analysing the learner context, analysing the learner and analysing the learning task. The analysis of the learning context can provide the instructional needs and a description of the different factors influencing the instruction. The purpose of the learner analysis is the characterisation of the end user of the instruction, which is in this case the middle school students. Conducting a context analysis and a learner analysis is also in concurrence with the Generic Model, which states that from the very beginning in the analysis phase the designer should already start with the implementation of the instruction (Plomp et al., 1992). In the task analysis the test specifications are written, with which the content of the instruction can be established. These three analyses are executed in the following three sections. As also can be seen in the Generic Model, it is important to start with evaluating the product already in the analysis phase. Therefore, the final section of this part describes the evaluation of the test specifications with an expert.

# Context Analysis

A learning task always takes place in a certain learning context, which in this case is the middle school. It entails not only the place, but also the temporal and social environment (Smith & Ragan, 2005). The analysis of the learning context can provide the instructional needs and a description of the different factors influencing the instruction. With the instructional needs, the designer can establish the main learning goals for the instruction. The description of the learning environment can provide the learning opportunities and constraints which have to be taken into account for the instruction.

## Needs Assessment

The first goal of the needs assessment is to investigate whether there exists a need for the instruction. Without a need, it would be a waste of resources to develop the instruction (Smith & Ragan, 2005). Next to this, it is conducted to better specify the need for the instruction. In the context of instruction, the assessment often results in a learning goal, which is the main goal of the instruction. This main goal is needed to continue the rest of the analyses, because all other analyses are conducted in respect to this goal. The goal can also be used to construct the summative evaluation, because when this goal is achieved, the instruction has proved to be successful.

Smith and Ragan (2005) identify three different models for the needs assessment, namely the problem model, the innovation model and the discrepancy model (see figure 2). The problem model is used when there exists a problem in the current system which has to be solved. As can be seen in figure 2, this model is to be used as a prerequisite for the other two models for assessment. With this model, it is determined whether there really is a problem, whether the cause of the problem is related to the performance of employees or to the achievement of learners, whether the solution to the problem is learning and whether instruction for these learning goals is currently offered. After the problem model, the needs assessment splits into the two other models. The innovation model is used when there is a new learning goal that the learners should achieve, and the discrepancy model is used when the already available instruction is not adequate to achieve the learning goal. The designer should choose one of these models for his needs assessment.

In the case of the instruction which will be constructed for this assignment, at first the problem model will be used to investigate the problem, and which of the two follow-up models should be used for the needs assessment.

### The problem

In the Netherlands, quantum mechanics always used to be a topic which schools themselves could choose to teach or not to teach. The only skill students had to know for the Centraal Eindexamen (the national central exams at the end of high school) which comes close to quantum mechanics is to elucidate the photoelectric effect and the wave-particle duality, mentioned within point 20 under subdomain E3 (Laan, 2013). However, one of the changes in the Centraal Eindexamen of 2016 was the addition of domain F1, which is called Quantum world (Groenen et al., 2014). For this subdomain the candidate has to be able to apply the wave-particle duality and the uncertainty principle of Heisenberg, and to explain the quantisation of energy levels in some examples with a simple quantum physical model. In order to give

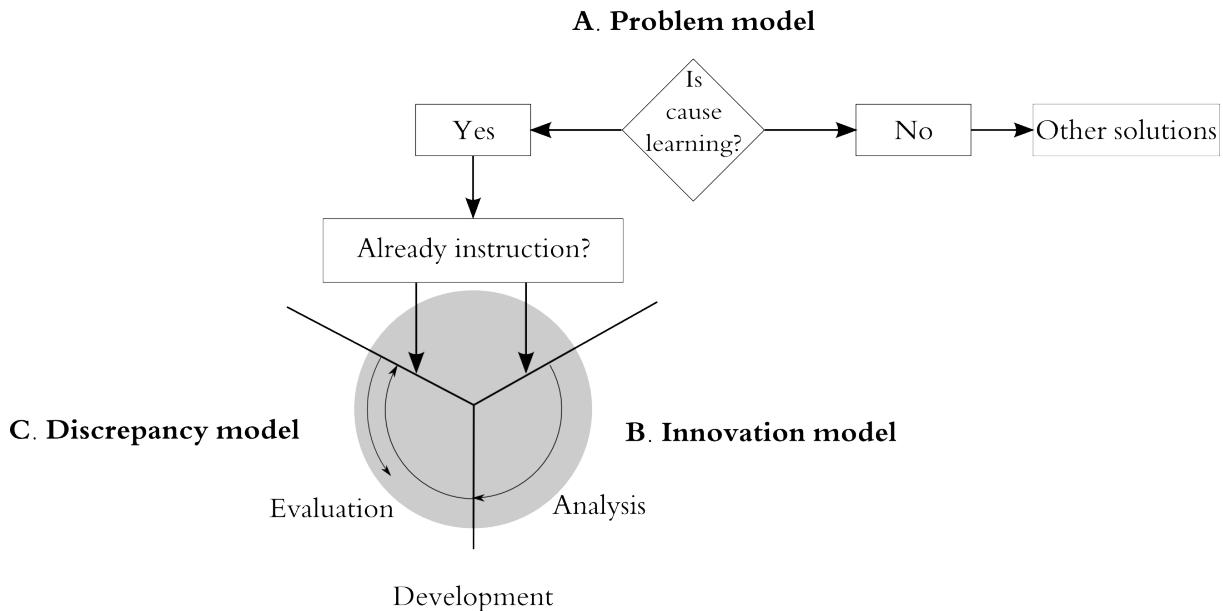


Figure 2: The three sides of needs assessment (Smith & Ragan, 2005)

all candidates a chance of passing this subdomain, schools have to alter their programs in order to meet the expectations of the Centraal Eindexamen.

However, when searching the internet using the search machine Google concerning the implementation of quantum mechanics in Dutch high schools, the quantity and the quality of the results are very low. There are also no results to be found in the Dutch papers. An example is the Dutch site <http://www.quantumuniverse.nl/>, where teachers can find a small amount of brief courses on fundamental quantum mechanics, and where the forums are very quiet with only 5 discussions, of which 4 are just started threads from the site administrator.

Upon finding this information, an expert was consulted to confirm this conjecture. The expert was researching the implementation of quantum mechanics on in Dutch secondary education, and is also a first degree physics teacher. She stated that within her school there were no initiatives to bring this topic in their classrooms, and that their school was no exception as well.

The fact that next year domain F1 has to be fully implemented and taught to all vwo students who chose physics as an examination subject is therefore slowly turning into a sword of Damocles. This stresses the urgency for the development of new course material. This is an example of extrinsic motivation. However, is there also intrinsic motivation to teach quantum mechanics on high schools? First of all, there is no article which claimed that quantum mechanics should not be taught on high schools. On the other hand there are but a few authors who did have some arguments in favour of teaching. Müller and Wiesner (2002) and Henriksen et al. (2014) state that quantum mechanics shapes our world view and that educated citizens should therefore become acquainted with the topic. It is also regarded as fundamental and should therefore be taught (Henriksen et al., 2014; Hobson, 2012). Finally, Erduran (2005) states that the teaching of philosophical themes in science education has been advocated for several decades, and quantum mechanics is one of these themes.

Because it involves new instruction, the innovation model will be used for the second part of this needs assessment.

### The innovation

The nature of the innovation lies within the change of the Centraal Eindexamen of 2016 in respect to the Centraal Eindexamen of 2015. The new additions within the domain Kwantumwereld outline the new goals of physics education in the Netherlands, and will be the ultimate goals for the students to achieve, and therefore be the ultimate learning goals for the students to achieve. This results in the following

learning goals (Groenen et al., 2014, p. 24-25):

”The candidate can:

- describe quantum phenomena in terms of the enclosure of a particle:
  - estimate whether quantum phenomena are to be expected by comparing the deBroglie-wavelength with the order of largeness of the enclosure of the particle;
  - apply the uncertainty principle of Heisenberg;
  - describe the quantum model of the hydrogen atom and calculate the possible energies of the hydrogen atom;
  - describe the quantum model of a particle in a one-dimensional energy well and calculate the possible energies of the particle;
  - Bohr radius, zero-point energy.
- describe the quantum-tunnel effect with a simple model and indicate how the chance of tunneling depends on the mass of the particle and the height and width of the energy-barrier,
  - minimal in the contexts of: Scanning Tunneling Microscope, alpha-decay.”

These goals confirm what the literature describes about the current appliance of quantum mechanics teaching within secondary, namely that often quantum mechanics is introduced with great emphasis on learning and practising algorithmic skills (Papaphotis & Tsaparlis, 2008a, 2008b). However, it is also found that high school students show higher interest in the conceptual aspects than the algorithmic aspects (Papaphotis & Tsaparlis, 2008a, 2008b; Levrini & Fantini, 2013). When focusing on the conceptual aspects, it engages students (Henriksen et al., 2014) and students start asking fundamental questions (McKagan et al., 2008). Furthermore, mathematical oriented approaches might be more common, however, quantum mechanics is regarded to be mathematically challenging (Gianino, 2008; McKagan et al., 2008), and most high school students lack proper background in mathematics at the required level (Dori, Dangur, Avargil, & Peskin, 2014). Because the usual focus on the algorithmic aspects, students often do not learn what instructors want them to learn (Asikainen & Hirvonen, 2014; McKagan et al., 2008), and improved student learning is possible by shifting the focus to conceptual understanding (McKagan et al., 2008).

Therefore, the aim of this instruction is to focus on a conceptual approach instead of a mathematical approach. Then, after the students have a sufficiently conceptual understanding of the material, the concurrent instructions in the curriculum can emphasise the goals stated by the Centraal Eindexamen of 2016, which adds the mathematical layer on top of the conceptual layer and can deepen the understanding of quantum mechanics. In summary, the main goal of this instruction is *to provide the student with a conceptual understanding of the different phenomena occurring in the realm of quantum mechanics*.

## Learning Environment

The learning environment description is the other major component of the learning context analysis (Smith & Ragan, 2005). The description contains information of all the external factors influencing the instruction. These are the mediators of the instruction, the already existing curricula which takes place in the environment, the available equipment available on the location of the instruction, the characteristics of the facilities at the location of the instruction, the characteristics of the organisation in which the instruction will take place, and the philosophies and taboos of the larger community in which this organisation exists.

A current first degree teacher training (*Cursussen Leraar Natuurkunde (Professional Master) Tilburg — Fontys*, 2015) does encompass quantum mechanics, so teachers which had this training should be familiar to the domain. However, Asikainen and Hirvonen (2014) states that teachers often still possess misconceptions about quantum mechanics, which are comparable to the misconceptions of the students

themselves. These misconceptions will be discussed in the learner analysis section on page 17. Experienced teachers who are teaching modern physics are more capable of teaching quantum mechanics (Asikainen & Hirvonen, 2014).

When implementing the instruction, the placement within the already existing curriculum is also important, because the instruction depends on prerequisites from other elements of the curriculum. The main prerequisite is knowledge of Bohr's atom model, because the different particles within this model are the particles on which quantum mechanics apply. This knowledge is taught in Domain E from the centraal eindexamen (Groenen et al., 2014), and because of the prerequisite, it is of upmost importance that this instruction is placed after Domain E in the existing curriculum. As already described in the needs assessment, the conceptual instruction could be followed by instruction of the mathematical aspects of quantum mechanics. Also, various experiments could be taught, which demonstrate the discovery of the various concepts introduced in the instruction and explain the different principles between the concepts. This could for example be the EPR experiment (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002; Velentzas, Halkia, & Skordoulis, 2007), which could lead to critical assessment of the realist and ontologist perceptions on quantum mechanics.

Another important aspect of the instructional environment is the method of delivery (Smith & Ragan, 2005). The recommendations for different aspects of the medium used for the delivery of the instruction entail interactivity, visualisation, the combination of different modes of representation, and the use of computation. By making it able to interact with the medium, it is possible for students to experiment with the different concepts, which gives way to inquiry learning (Adegoke, 2012; Asikainen & Hirvonen, 2014; Dori et al., 2014; McKagan et al., 2008). Visualisation is a powerful tool, and can make the matter less abstract (Dori et al., 2014; Henriksen et al., 2014; McKagan et al., 2008). It also is easier to build mental models of quantum mechanics. Levrini and Fantini (2013) warns however against the use of oversimplified visualisations, because pictures are extremely partial and can be misleading. Therefore, it is important that the visualisation does not entail any unnecessary simplified representation of the matter. This combined with other different modes of representation, for example a textual description of the concept, makes it possible for the student to complete their mental model (Dori et al., 2014). Finally, the use of computation makes it possible to take away the mathematical complexity from quantum mechanics, making way for a purely conceptual approach (Barnes, Garner, & Reid, 2004; McKagan et al., 2008; Velentzas et al., 2007).

One could combine all these aspects by using simulations, which is also recommended by McKagan et al. (2008). However, teachers often prefer traditional lectures, because that is easier to implement in their classroom (Adegoke, 2012). This difficulty has to be overcome if quantum mechanics is to be implemented successfully in the classroom. Furthermore, it has to be investigated whether the sufficient hardware is available in the learning environment.

Finally, it is important to investigate whether the instruction fits in with the mission and vision of the school, and also the philosophies and taboos that the teachers hold. Therefore, it is advised to find these discrepancies by the means of interviews, in which the school board is asked about their mission and vision, and the teachers about their personal beliefs in regard to quantum mechanics.

In any case, this assignment does not look into the implementation of the instruction yet, so these factors have to be investigated further when embedding the instruction in the context of a specific school.

# Learner Analysis

The second analysis is that of the learners (Smith & Ragan, 2005). The purpose of this analysis is the characterisation of the end user of the instruction, which is in this case the students of secondary education in the Netherlands, mostly ranging from age 17 to 18. This analysis will focus itself on the general misconceptions held by members of this demographic.

When developing an instruction, it is important to consider the already available conceptions on the topic. In quantum mechanics, these preconceived models often prove to be incorrect (Asikainen & Hirvonen, 2014; Papaphotis & Tsaparlis, 2008b; Thacker, 2003). This partly comes from the nature of quantum theory (Papaphotis & Tsaparlis, 2008b), but also partly from textbooks and instruction (Hubber, 2006; Papaphotis & Tsaparlis, 2008b). The problems often stem from depending on outdated deterministic or realist models (Hubber, 2006; Papaphotis & Tsaparlis, 2008a, 2008b), an often mentioned example of this is that students often mix up the deterministic planetary model with the indeterministic atom model (Dori et al., 2014; Henriksen et al., 2014; Hubber, 2006; Müller & Wiesner, 2002; Papaphotis & Tsaparlis, 2008a, 2008b). McKagan et al. (2008) also mentions that it is difficult for students to recognise the scale in which quantum mechanics take place.

Thacker (2003) describes how much knowledge of students consists out of memorised facts, for example that light is a wave and electrons are particles. When the student then is confronted with new or different information from what they know, they develop new memorised facts instead of creating the right model. This then results in models consistent with fragmented models of microscopic processes, which are often incorrect but self-consistent with a certain experiment (Hubber, 2006; Thacker, 2003). When the student cannot model the fragments anymore, this can result in deep skepticism towards quantum mechanics (Barnes et al., 2004; Henriksen et al., 2014; Levrini & Fantini, 2013). Müller and Wiesner (2002) has created a long list of exact conceptions students hold about microscopic phenomena, which are too detailed to enlist fully in this article.

The misconceptions described in the studied articles mostly are measured in relation to the teaching material which is currently employed within schools or universities. This material is already described in the Topics mentioned in Literature appendix (see page 79), and can generally described as misconceptions in relation to the Rutherford-Bohr model of the atom, and in relation to experiments like the double-slit experiment. However, it would be interesting to investigate the misconceptions in relation to the fundamental concepts of quantum mechanics themselves, for example in relation to elementary particles, superposition, random collapse of the probability function and entanglement. This would give greater insight in the conceptual understanding of students. However, no research has been conducted in these areas thus far.

In conclusion, most of the preconceptions of students prove to be incorrect, stemming often from quantum theory or textbooks. These preconceptions often contain outdated deterministic or realist models. Furthermore, it is difficult for students to understand the scale. Finally, knowledge consists out of memorised facts, which then form fragmented and incorrect but self-consistent models. Conflicts between these models can result in skepticism.

# Task Analysis

The final step is analysing the learning task (Smith & Ragan, 2005). In this analysis the goals from the needs assessment during the analysis of the learning context have to be translated to test specifications, with which the content of the instruction can be established. To establish these test specifications, it is important to investigate the learning goal first. This will be followed by a description of the various strategies mentioned within the literature for how to teach quantum mechanics. The next step is the prerequisite analysis, which is a description of the prerequisite knowledge the students have to possess in order to partake in this instruction in relation to the content, described in the Topics mentioned in literature appendix on page 79. After that, the learning objectives can be written, which model the outline of the instruction. Finally, the test specifications are formulated, which can be used to measure the student his understanding of quantum mechanics after the instruction.

## Learning goal

The main learning goal as specified needs assessment using the innovation model from page 14, the instruction will pursue provide the student with a conceptual understanding of the different phenomena occurring in the realm of quantum mechanics. This goal will be the main guideline for the information-processing analysis. However, it will not be possible to provide the students with a complete conceptual understanding of quantum mechanics. First of all, even though the scientific community has an understanding of quantum mechanics, it is not fully complete. Second to that, physics students in secondary education do not have the time needed to gain at least the complete conceptual understanding of quantum mechanics available from the scientific community. Finally, there is not enough time to design an instruction which achieves a complete conceptual understanding, and the time available for this instruction is also limited. Therefore a choice has to be made in the different topics being taught.

Furthermore, there exists a consensus within the studied articles that quantum mechanics is a difficult topic, and this is also a consensus among educators (Gianino, 2008; Papaphotis & Tsaparlis, 2008a, 2008b). There are a couple of reasons mentioned within the articles to explain this topical difficulty. A couple of sources state that quantum mechanics is a very counter intuitive topic (Henriksen et al., 2014; Levrini & Fantini, 2013; McKagan et al., 2008; Singh, Belloni, & Christian, 2006), because it contradicts many aspects of our daily experience, like locality or determinism. Quantum mechanics is also considered to be a very abstract topic (Barnes et al., 2004; Gianino, 2008; McKagan et al., 2008; Papaphotis & Tsaparlis, 2008a; Singh, 2006). Because quantum mechanics differs a lot from our everyday experiences and because of its abstractness, it is difficult for learners to visualise the concepts of quantum mechanics (Henriksen et al., 2014; McKagan et al., 2008). Another factor contributing to the difficulty of quantum mechanics is that it is mathematically challenging (Gianino, 2008; McKagan et al., 2008), it involves mathematical skills that most high school students — even vwo 6 students — do not possess. Because of the difficulties stemming from teaching quantum mechanics, it would be better to teach concentrate on teaching a few topics of quantum mechanics in a way that it can be understood, rather than trying to teach as much as possible in the limited time available.

## Teaching strategies

The literature provides a lot of strategies which can be used to teach quantum mechanics. There are recommendations for which content to use. Some of the strategies focus on meta-cognitive aspects. Finally, there are a few frameworks which can be used to teach modern physics.

Some of the content-related strategies emphasise the importance of embedding the instruction in real-world contexts, for they help with understanding (McKagan et al., 2008; Thacker, 2003; Dori et al., 2014) and help appreciate the relevance of quantum mechanics (Barnes et al., 2004; Henriksen et al., 2014; McKagan et al., 2008). Furthermore, Thacker (2003) suggests introducing microscopic processes as an integral part of a study of electricity and magnetism. This could help demystify the topic, which also would contribute towards a better understanding (Barnes et al., 2004; Müller & Wiesner, 2002). An example of how this can be done is by using the e/m experiment, where the electromagnetic effect is demonstrated by the properties of electrons. Furthermore, the language of physics is important (Henriksen et al., 2014), and should be used carefully (McKagan et al., 2008). The consulted articles all recommend a conceptual approach above a mathematical-oriented approach. Mathematical-oriented approaches might be more common, but most high school students lack proper background in mathematics at the required level (Dori et al., 2014). Barnes et al. (2004) and Henriksen et al. (2014) believe teaching through history of science is believed to be constructive.

Papaphotis and Tsaparlis (2008a) states that critical thinking skills are crucial for understanding quantum mechanics, because students have to investigate the new material in a critical way to build the correct mental models. Active learning also contributes to investigation of the material. Because the students easily build misconception, right feedback is vital to prevent misconceptions and can stimulate students to build correct mental models. Finally, Papaphotis and Tsaparlis (2008a) suggests collaboration, which is also suggested by Adegoke (2012) and Barnes et al. (2004). Collaboration could lead to peers providing each other with critical questions and feedback. Especially in the case of female students this could benefit to learning quantum mechanics (Adegoke, 2012).

The frameworks mentioned by different authors are directly or very similar to thought experiments (Asikainen & Hirvonen, 2014; Erduran, 2005; Levrini & Fantini, 2013; Velentzas et al., 2007). Asikainen describes the most elaborated framework for a well-conducted thought experiment, which includes the steps question and general assumptions, description of the features of the system, performance of the thought experiment itself, extraction of the results and drawing conclusions. Erduran (2005) and Levrini and Fantini (2013) also describe a framework, but the steps they mention already overlap with those of Asikainen and Hirvonen (2014).

## Prerequisite analysis

Furthermore, it is important to look at the pre-existing knowledge about quantum mechanics of the students. According to the Centraal Eindexamen 2016 (Groenen et al., 2014), the candidate should already have learned the Rutherford-Bohr Model of the Atom, and this is earlier already specified as prerequisite of the instruction. This means that the students have knowledge of at least two elementary particles, namely the photon and the electron, and their place within the atom. They also should know about the nucleus and the shell of an atom, and about protons and neutrons. Furthermore, it could be that the students already learned about the double-slit experiment (Laan, 2013), although it would be better if the students get instruction about this experiment after this instruction. This is because at that point they will be familiar with terms like superposition and observer dependency, which are necessary to fully comprehend the double-slit experiment. Finally, the students could have learned about some of the concepts of quantum mechanics outside of the standard curriculum, like for example via science magazines. However, for this instruction it will be presumed that they have no knowledge of these concepts, for the reason that they have not been taught in the standard curriculum.

## Learning objectives

Zeilinger (2005) provides a clear conceptual understanding of some of the phenomena occurring within quantum mechanics. The first step was to summarise this book, so learning objectives could be extracted from this book. This summary was then translated into a unidirectional dependency graph, which means that the different elements of the summary were projected into nodes, and the edges between these elements displayed a logical order of teaching the different elements. These elements were then extended by using the taxonomy of Bloom (Bloom, Englehart, Furst, Hill, & Hrathwohl, 1956) (see figure 3). This taxonomy describes six levels of learning objectives, which are Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. Before a higher level objective can be reached, all lower level relevant to that objectives have to be achieved first. Every level also has his own defined action verbs which have to be used for writing the objective. For example, Knowledge level objectives use action verbs such as "state" and "list", whereas Comprehension level objectives use verbs such as "explain" and "differentiate".

Using the taxonomy of Bloom made the different elements better defined and also displayed better in which order the student should master the learning objectives. The graph cannot be easily displayed on a4 format, this is why it was translated to a table which displays each topics and its prerequisite. This table is included in the appendix *Learning Objectives* on page 85. However, a prerequisite graph has been included in the Prerequisite Graph of the Topical Domains appendix on page ??.

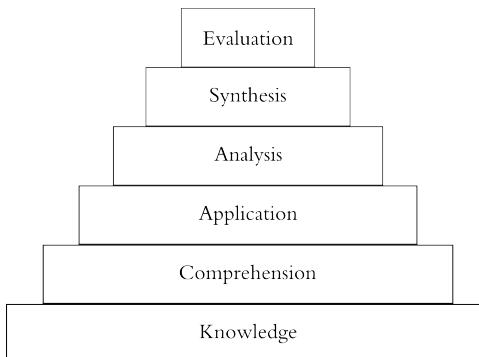


Figure 3: The taxonomy of Bloom (Bloom et al., 1956)

36 of the learning objectives fall into the knowledge domain within the taxonomy of Bloom, 15 learning objectives fall into the comprehension domain, 3 learning objectives into the application domain, and 2 objectives into the analysis domain. The reason why most of the learning objectives fall into the knowledge domain is because the topic of quantum mechanics is mainly new to the high school student. Because of this, the student first has to learn a lot of new terms and definitions before he can actually comprehend quantum mechanics, for having knowledge is a prerequisite for an eventual understanding of the concepts. However, the main goal of the instruction is comprehension of the concepts, even if there are only 15 learning objectives within this domain, for comprehension leads to conceptual understanding. Application and Analysis is less relevant, this would be more relevant to principle learning, which would be important for learning the algorithmic aspects of quantum mechanics. Any higher domains cannot be reached, for they require mastery of the application and analysis domain. However, this could be achieved next in the curriculum.

Furthermore, the learning objectives are also categorised by topical domains, which are Applications of Quantum Mechanics, Preknowledge, Elementary Particles, Classical Communication, Observation Dependency, Realism and Ontology, Superposition, Entanglement, Uncertainty Principle of Heisenberg and Teleportation. These are elaborated in the Topical Domains appendix on page 82, and a prerequisite graph of these domains is displayed in figure 9 on page 84, embedded in a curriculum with other topical domains.

## Test specifications

Every learning objective has to contain a description of the terminal behaviour or actions that will demonstrate learning, a description of the conditions of demonstration of that action and a description of the standard or criterion (Smith & Ragan, 2005). The description of the terminal behaviour is already specified in the *Learning Objectives* appendix on page 85. If a condition is present for the execution of the learning objective, this is already specified as well, most of the time using the word "given". However, the standards or criteria for measuring specifying how the learning objective has to be achieved by the student are not yet included in the table.

Thinking about the criteria or standards on beforehand can be very useful for the designer, for he then also has an idea for how specific the instruction text should be written. Therefore, a list with the standards given a certain learning objective has also been included, in the *Learning Objectives and Standards* appendix on page 89. The objectives are indicated by numbers, and the standards by letters. The standards are formulated as the behaviour the student should display upon measurement of the learning objective. Some of the learning objectives are formulated in such a way that further specification by standards is not necessary, for example learning objective 2: "The student can state that everything we observe exists out of molecules". The test specifications can also be used for the screening evaluation (Nieveen, Folmer, & Vielgen, 2012), which will be conducted after the development of the instruction in order to review whether all specifications are met in the instruction (see the Evaluation Matchboard appendix on page 127).

# Focus Group Evaluation

To ensure that the instruction would not contain errors on the subject of quantum mechanics, an expert was consulted to look at the learning objectives and criteria. The expert consulted is a part-time PhD student which researched the implementation of quantum mechanics in the curriculum of Dutch secondary education, and a part-time first grade physics teacher. The same expert was also consulted during the Needs Assessment (see page 13). For this evaluation, a focus group evaluation was conducted (Nieveen et al., 2012). With the walkthrough, the design proposal was checked on factual errors, using an interview with the expert. The result of the walkthrough would be an evaluation of the relevancy and the consistency of the product (see the *Evaluation Matchboard* appendix on page 127), which entailed going through all the learning objectives and standards. Although she gave feedback on the specific formulation of some of the learning objectives or criteria, she did not find any factual errors. She did give some feedback on which learning objectives might not be considered to be preknowledge, such as learning objective 8: "The student can state the value of the reduced Planck Constant".

# Design

The second phase of the Generic Model is the Design phase (Plomp et al., 1992) (see figure 1 on page 10). In this phase, the results from the Analysis phase are translated into design principles and an outline of the instruction that can be used directly for the development of the instruction. This chapter will start out with the relevant conclusions which are drawn from the analysis phase in order to summarise the results and translate them to the context of the product, the instruction. After the summary, an active choice still has to be made about the medium to use for delivering the instruction. This will be done in the next section according to the results relevant to the choice of the medium. The remaining conclusions will then be used to formulate design principles, which facilitate the concrete use of the results from the analysis. Furthermore, design principles can be used after the development for a screening evaluation (Nieveen et al., 2012) (see the Evaluation Matchboard appendix on page 127). Finally, the different learning objectives formulated during the task analysis have to be ordered into an outline of the instruction, so the designer can directly translate them into text or other means of instruction.

# Conclusions from the Analysis

There is a wide variety of topics available for quantum mechanics education. It is advisable to start any instruction with the Rutherford-Bohr model of the Atom and its relation to elementary particles, for this is the scale on which quantum mechanics take place. A next step could be introducing the different phenomena which happen on a quantum scale, such as superposition, observer dependency and entanglement. One way to introduce superposition and observer dependency is by using the double-slit experiment. This also teaches about the wave-particle duality of elementary particles. Furthermore, the students could be taught the differences between classical mechanics and quantum mechanics, which are determinism and probabilism, locality and non-locality, and continuous and discrete distances. One way to highlight the strangeness of quantum mechanics is by using the debate between realism and ontology, which emphasises that quantum mechanics are different than a student might think at first. There are also famous thought experiments, for example Schrödinger's cat, which could be used to create different mental models with the students. Finally, there are some mathematical approaches to quantum mechanics, however there is a consensus within educators that a conceptual approach is more effective.

Only a few amount of studies writes about the motivation for teaching quantum mechanics on secondary education. There is however no study which claimed it should not be taught. Reasons why it should be taught are that educated citizens should be acquainted with quantum mechanics and that it is regarded fundamental.

Quantum mechanics is regarded to be a difficult topic, because it is counter intuitive, it contradicts daily experienced locality and determinism, it is regarded to be abstract, it is difficult to visualise and it is mathematically challenging.

Misconceptions about quantum mechanics can arise out of the nature of quantum theory, but also from textbooks and previous instruction. It is important that the information handed to the students are not simplified, because this can lead to misconceptions. Problems also often originate from outdated deterministic or realist models. The students therefore have to be confronted with the fact that their own models cannot be applied in the context of quantum mechanics. Students also find it difficult to recognise the scale in which quantum mechanics take place. Hence, the students should be informed that quantum mechanics take place on the scale of elementary particles. Knowledge of students often consists out of memorised facts, and when confronted with new or different information, new facts are memorised instead of creating right models. This results in fragmented incorrect but self-consistent models. Because of this, the instruction should provide the student with a coherent description of quantum mechanics.

The literature prescribes different strategies for teaching quantum mechanics, namely recommendations for content, aspects of the medium to use, meta-cognitive aspects and a framework. Content related strategies entail embedding the instruction in real-world contexts, letting the student appreciate the relevance of quantum mechanics, introducing microscopic processes as an integral part of electricity and magnetism, using the language of physics, and using an conceptual approach instead of a mathematical approach. The medium used should be interactive, it should visualise the concepts, it should make use of different modes of representation, and it should make use of computation. It should be noted however that one should be careful with visualisation, for this can easily lead to misconceptions. The use of simulations are suggested. Furthermore, critical thinking skills, active learning, feedback and collaborative learning could contribute to students building the correct mental models of how quantum mechanics work. Finally, thought experiments are regarded to be very effective for learning quantum mechanics,

this entails questions and general assumptions, a description of the features of the system, performance of the thought experiment itself, extraction of the results and drawing conclusions.

In secondary education, instructions often emphasise learning and practising algorithmic skills. This however clashes with the recommendations from the literature, which advocates an emphasis on conceptual understanding. It is also found that students show higher interest in conceptual aspects than the algorithmic aspects. Conceptual approaches engage students and probes the student to ask fundamental questions. Because of the focus on algorithmic aspects, students currently often do not learn what is intended by the developer of the instruction, improved student learning might be possible by shifting the focus to conceptual understanding. This is why the learning objectives are all targeted towards a better conceptual understanding of the student, without having to rely on complex mathematics or experiments. The different domains which will be taught are Applications of Quantum Mechanics, Preknowledge, Elementary Particles, Classical Communication, Observation Dependency, Realism and Ontology, Superposition, Entanglement, and the Uncertainty Principle of Heisenberg. These Domains will then be combined within the experiment of Quantum Teleportation.

# Method of Delivery

## Requirements for the Method of Delivery

The analysis phase provides a couple of recommendations or requirements for the medium used to deliver the instruction:

- The medium should be able to visualise the content;
- The medium should allow interaction;
- The medium should take away the mathematical difficulty, for example by using computation.
- The medium should be able to use different modes of representation;

As already stated within the Analysis chapter, these requirements cannot be reached by relying on traditional means of instruction such as text books, pictures and lectures from a teacher. It is not possible for a student to interact with the contents of a book or with pictures, and lectures from a teacher often entail the teacher standing in front of the class and telling the students about quantum mechanics in a supplantive way. Of course it would be possible for a student to ask questions, but more room for interaction is needed to be even more successful, and the teacher has not enough time to facilitate interactive learning to every student in a differentiated way.

One of the suggestions from the studied literature entailed using simulations, because these could provide all of the requirements. However, simulations often are related to certain experiments, for example by simulating the double-slit experiment and providing the student with data such as visuals or numerals. This is in contrast with the requirements from the task analysis, which specify that rather than teaching by means of experiments, the instruction should first teach about the concepts themselves in a more direct way.

Another way of teaching quantum mechanics via electronic media would be to deliver the instruction by using game-based learning. Game-based learning refers to the use of games for educational purposes. Relatively speaking, only little research has been carried out to investigate game-based learning, but recent reviews revealed a potential of games being an effective tool for instruction, "even more effective than conventional instruction" (Wouters & van Oostendorp, 2012, p. 1). In order for game-based learning to take place, the game has to supersede sole entertainment purposes by having an educational value, so that the student learns something about the real world by playing the game. Examples of these games are historical games like Assassin's Creed, Age of Empires or Valiant Hearts, in which the student is exposed to certain historical events or figures, or puzzle games like Portal, in which the student develops an understanding about physics. However, these games are often only intended for entertainment purposes and are only tangentially fit for educational purposes. Most research within game-based learning is conducted on games which are specifically designed to have an educational value. These games often contain explicit formulated learning goals which can be tested by pre- and post-testing. They are designed with the primary goal of education rather than entertainment, and are therefore a subset of Serious Games. This term refers to the set of games designed for a primary goal other than pure entertainment. This goal can be teaching, but also raising awareness about a certain topic or persuading the student to believe something.

One disadvantage for using game-based learning is that it takes a lot of time to develop games in general, and none of the available games can be directly used for teaching the learning objectives specified in the Task Analysis. However, there already exists an easy to use game which can be used to create an environment in which quantum mechanics can be taught on a conceptual level. This engine is qCraft, developed as a modification for the game Minecraft.

## Minecraft

Minecraft is a game initiated by Marcus Persson (also known as Notch), further developed by Mojang AB, and now property of Microsoft. There are different versions for different platforms available, and the main version is being developed for Windows, Mac OS X and Linux. It is the third-best sold game of all time, and the best sold game for PC with 70 million sold copies at the time of writing.

The game is a first person sandbox survival game, available for playing both in single-player and multiplayer. In the game, the player walks around in a procedurally generated world fully made out of blocks which are one cubic meter in size (see figure 4). The player can control his avatar similar to other first person games, by using the WASD keys for moving and using the mouse for looking around. The unique feature of the game is that the player can place and remove blocks for himself. Each block also has a specific block-type, which gives it a certain appearance and sometimes also a special physical attribute. For example, blocks with the sand block-type always fall down unless being on top of another block. Some blocks also emit a signal, which can be used to trigger certain commands or for example open a door to a room.



Figure 4: A screenshot within the game Minceraft, where a player created structure is placed within the procedurally generated terrain.

Minecraft is an easy to use engine for delivering instructions as well. It has support for signs with text and pictures which can be placed in the world, books the player can open and read, and commands which can be used to move the player to certain areas in the world or giving the player certain items. There is even a special version of Minecraft for use in classrooms, which is called MinecraftEdu ([minecraftedu.com](http://minecraftedu.com)), and it is used by teachers around the world.

## qCraft

In order to use Minecraft to players, a certain modification of the game has to be installed. This modification is also available for MinecraftEdu, which makes it easier to use for teachers. It introduces special types of blocks into the game, which are Observer Dependent Blocks and Quantum Blocks. The Quantum Blocks behave in a way similar to elementary particles, which is that every time a Quantum Block is observed, it first is in a green "in-between state" and then takes on one of two block-types at random. An observation takes place every time the player looks at it. For example, if a player looks at a Quantum Block, it can collapse 50% of the time to a gold block-type and 50% of the time to a diamond block-type. The green colour the block takes on before collapsing to either of the two block-types represents the fact that the block is in superposition before measurement.

An Observer Dependent Block has one difference with the Quantum Block, which is that its block-type does not collapse at random, but that the collapse is determined by the angle the block is observed from. This block is added to the game in order to learn the player observer dependency, without also having to explain the random collapse.

Quantum Blocks can also be entangled with each other. This means that every time one of the entangled blocks is observed, all Quantum Blocks their block-type collapse to the same value. Only the boson type of entanglement is implemented yet.

Furthermore, the modification adds a couple of tools to interact with the blocks. It adds two types of goggles, which are the Quantum Goggles and the Anti-Observation Goggles. The Quantum Goggles highlight all of the special blocks by giving it a fluorescent green colour, by which the player can easily identify all of the qCraft blocks present around him. The Anti-Observation Goggles prevent the player from generating observations to the qCraft blocks. Another tool provided by qCraft is the Automatic Observer, which can be activated to generate an observation to the qCraft block attached to the Automatic Observer.

## Possibilities of using qCraft for teaching quantum mechanics

First of all, qCraft meets all the requirements earlier specified based on recommendations by the studied literature. It is interactive, because the student can move around in the world instead of being a passive observer. This allows for walking around the qCraft block, observing them in different ways, trying to find the patterns, and even trigger mechanisms based on the collapse of the block type of the qCraft block. Furthermore, the mechanics introduced by qCraft make quantum mechanics visible. The student can see what observer dependency means for a Quantum Block, and how boson type entanglement works between multiple Quantum Blocks. One of the advantages of using Quantum Blocks is that they already demonstrate the correct behaviour, so there is no need to rely on thought experiments such as Schrödinger's Cat. The student can observe the behaviour directly, and can therefore experiment with it without needing an external analogy. Minecraft also allows for different modes of representation. Next to the qCraft blocks, it is also possible to hang pictures in the world, to place text on signs, and to add books into the world. This allows for explaining the students the specific behaviour of the blocks and to transfer this to real quantum mechanics by comparing it to the behaviour of elementary particles. Additionally, the only mathematical comprehension the student needs in order to understand the behaviour of the blocks is that the block types collapse to a random state, without having to comprehend difficult probability functions which require mathematical skills which students of secondary education do not possess.

Furthermore, Minecraft can be used to make a tailor-made learning environment, because it is possible to place or remove blocks in any way the instructor sees fit. Therefore, the instructor can build specific room designs which can be used to provide the player with a learning environment fitting to meet specific learning objectives. The instructor can also provide the student with texts by placing signs and books into the environment. The command blocks and logic circuits could be used in order to force the student to do something within the learning environment in order to progress into the next section, for

example by placing an iron door which only opens after the student has achieved something in a room.

Finally, all of the learning objectives can be achieved using only qCraft, without having to rely on more external sources of delivery. One disadvantage of using qCraft is that it is not possible to visualise the double-slit experiment for example. However, it was already stated in the Analysis phase that this experiment would occur only after a conceptual understanding was achieved with the student, and that it could be introduced later on in the curriculum. The debate between realism and ontology can be described within a book. The uncertainty principle of Heisenberg cannot be emulated within qCraft. However, it is possible to display the different variables within the formula on images situated in the world. This way the student can learn the formula by means of discovery learning. The experiment of teleportation is visualisable in qCraft, for the only concepts needed are random collapse and entanglement.

Another advantage of using qCraft is its accessibility. A lot of people already play Minecraft, and this could be an attractive entrance into the world of quantum mechanics. There are also a lot of gamers who have not yet played Minecraft, but are still quite familiar with the controls because they have played other first person games. However, there will also be students who are not familiar with first person games, so a tutorial teaching the controls of Minecraft will still be needed at the beginning of the instruction.

## Comparison of different methods of delivery

To summarise this section, table 1 was composed, displaying the different possibilities of the different methods of delivery. In this table, traditional instruction is split up into teacher lectures and written instruction. Teacher lectures refer to instruction delivered by a teacher standing in front of a classroom. Furthermore, written instruction entails instruction delivered on paper, for example by a textbook. The simulations refer only to computer simulations, for example simulations of the double-slit experiment. The term "top of the shelf game" refers to games already available on the market. qCraft is enlisted separately from other available games.

	Teacher lectures	Written instruction	Simulations	Top of the shelf game	qCraft
Freedom of content delivery	X	X			X
Easy to implement	X	X			
Mathematical understanding	X	X	X		
Visualisation		X	X	X	X
Interaction			X	X	X
Computation			X	X	X
Entertainment value				X	X

Table 1: The different methods of delivery and their possibilities.

One feature that traditional delivery methods have over typically available computer simulations or games is the freedom of content delivery. This entails the freedom the instructor has to design the instruction in such a way that it meets the requirements and purposes needed in the context of the implementation. For example, if available written instruction is used in a specific context, the instructor can omit certain parts from or add other parts to the instruction. This is the one feature that sets qCraft apart from other available games, for it is possible for the instructor to open Minecraft and adjust the map to meet the needs of the instruction.

As already stated in the learning environment section within the Context analysis (see page 15), teachers find it easier to implement traditional methods of delivery than computer-based methods of delivery. Because of this, the methods currently used within physics education are delivered by traditional methods. Therefore, when choosing for computer-based methods, it is important that extra instruction is delivered for the teacher with computer-based methods in order to embed the instruction within the teaching context. Furthermore, the necessary hardware and software has to be available to the teacher.

Mathematical instruction is a form of instruction often employed within traditional physics lectures. Teaching the students principles which define the relationships between certain concepts can be practiced during lectures or by the students themselves with explanations and exercises presented in a textbook. Mathematical principles can also be taught by using simulations, where students can adjust certain variables which then have a visible effect on other variables, providing a more intuitive understanding of the principles. However, this instruction only focuses on the conceptual understanding, and therefore this aspect is less relevant for the choice of the method of delivery.

In traditional lectures, it is not possible to visualise the concepts within quantum mechanics, because it relies on oral instruction. However, if present, the teacher can make use of sheets in order to visualise the concepts. In written instruction, images can be presented to the students. However, it is not possible to animate the concepts, which is also an important factor of visualisation. Computer simulations and games provide mainly animated visualisation. However, the instructor has to be careful when using visualisation, for it can lead to misconceptions if used incorrectly.

Interaction is more difficult in traditional lectures, and is not possible in written instruction. The only way to provide interaction in a classroom is to answer certain questions the students have about the instruction. Interaction is the core mechanic of computer simulations and games, for it heavily relies on the actions of the student.

When using traditional instruction methods, all computation has to be performed by hand or by using a calculator. The calculator might seem to be an easy way of avoiding the need for computation by hand, but in order to use the calculator the student still needs to be able to understand the mathematical background, and therefore still proves to be a problem for secondary derivatives needed for the Schrödinger equation. A computer can take away this problem by doing the computation for the student and thereby leave out the mathematics.

The requirement for multiple modes of representations is not displayed in the table, for this relies on combining multiple methods of delivery in one instruction or curriculum. Teachers often do not only rely on lectures, but also use books and sometimes multimedia as well in order to teach certain information. This is an important aspect for the implementation of the instruction, but not for the choice of a certain method of delivery. However, when developing the instruction, it is important to combine multiple modes if possible.

Finally, computer games tend to have a higher entertainment value than the other methods of delivery. As stated before, it is not the main goal of a serious game to entertain the student. However, it can still help the student to engage itself in the activity, which also could contribute to the learning effect of the instruction.

As can be seen in the table, all of the relevant requirements for the instruction are met within the qCraft modification of Minecraft. Therefore, this instruction will make use of this method of delivery.

# Design Principles

Most of the recommendations from the studied literature are already covered by the choice of learning objectives and the choice for qCraft. Other recommendations are not directly relevant to the design of the instruction, for they are recommendations relevant to the implementation of the instruction, which will not be done within this project. However, there are still a couple of recommendations which are still relevant for consideration during the development phase. Therefore, these recommendations have been translated into a list of design principle in the list below.

1. The information handed to the student are not allowed to be simplified, for this can lead to misconceptions
2. The language of physics has to be used to teach students the concepts within quantum mechanics
3. The different concepts have to be connected with each other
4. Each concept should be transferred to the real-world context of the behaviour of elementary particles
5. The instruction has to be mathematically accessible towards the student and should not require mathematical skills beyond those of physics student within upper secondary education
6. Students have to be triggered to reconsider their realist or deterministic models of physics in the context of quantum mechanics
7. The student has to be asked to extract results from his own observations
8. The student has to be asked to draw conclusions from the extraction of the results
9. The student has to get feedback on the conclusions he has drawn
10. The student has to be triggered into questioning his knowledge of physics based on the conclusions he has drawn from his observations

Someone might notice that the design principles are quite broadly defined, whereas normal design principles are formulated in a more concrete way. However, due to the nature of this project, the only source for these design principles are the recommendations by the literature. As such, the concreteness of the design principles are dependent on how concrete the recommendations are defined within the articles. Still, these design principles can be used as general guidelines for developing the instruction.

Design principle 1 is especially relevant when visualising any concepts for the reader. This might be especially relevant when depicting the Rutherford-Bohr model of the Atom, for this easily leads to a conception of an electron orbiting around the nucleus, whereas the electron is just somewhere in the shell and not at a specific location in orbit with a specific speed. A way around this is by using figure 8 on page 79, for this displays only the nucleus and the shell without an electron particle.

To provide the students with handles to internalise the concepts, the terminology of quantum physics will be used as specified in principle 2. The aim of principle 3 is preventing fragmented incorrect but self-consistent models. By connecting and combining the different concepts, the student is able to build

one holistic model of quantum mechanics, instead of developing disconnected models about different experiments. A way to connect the concepts is by repeating the concepts, actively explaining the relations between the concepts and finally combining all of the concepts in the teleportation experiment. Another way to connect the different concepts is by relating them all to the behaviour of elementary particles, which is stated in principle 4. This also places the concepts in a context which is familiar to the student, for he already learned about electrons and photons earlier during physics lessons.

The design principle 5 related to the mathematical level is probably already covered by the choice of learning objectives and the choice of medium of delivery. However, it still remains an important requirement for the instruction because most current instructions make the mistake of underestimating the mathematics, and it is therefore included.

Design principle 6 and 10 are important to help the student realise the counterintuitive aspects of quantum mechanics. This can be achieved by asking the student questions about the material and about his own beliefs. Principles 7 and 8 then trigger the students to actively build new mental models about physics. Finally, design principle 9 provides the students with feedback on their newly built mental models, so they can adjust them towards a more correct model.

The design principles not only provide a use during the development of the instruction, but will also be used in a screening evaluation after the development of the instruction (Nieveen et al., 2012) (see the Evaluation Matchboard appendix on page 127).

# Framework for the Instruction

The last step of the design phase is to structure the learning objectives specified in the task analysis and displayed in the Learning Objectives appendix on page 85 in such a way that the instruction can be written. This is achieved by developing a framework, which gives the designer concrete steps for how to develop the instruction.

## Events of instruction

A generic framework for writing instructions are the events of instruction (Smith & Ragan, 2005), which are displayed in table 2. These events are normally used for traditional instruction methods such as teacher lectures. However, as many of the learning objectives still rely on textual instruction, and as it is possible in Minecraft to provide books to the student, the expanded events of instruction can still be applied in this context. Furthermore, teachers should already be familiar with the expanded events of instruction, so using them would facilitate the implementation of the instruction within secondary education. The events are divided into four main parts: the introduction, the body, the conclusion and the assessment. The introduction serves to trigger the student into having an active learning attitude. This is achieved by gaining the attention of the student, inform the student about the purpose of the instruction, motivating the student, and previewing the learning activity.

Then, within the body of the instruction, the actual content of the instruction is delivered. Before delivering the new content, first the relevant prior knowledge of the student has to be recalled, because this way the student can connect the new content with what he already knows about the topic, and because this way the relevant brain regions get activated. This allows the student to be better capable of processing the new content. After the relevant prior knowledge is recalled, new information can be provided. After this, the attention of the student has to be focused on the most important aspects of the new information. This way the student understands the information most important to remember, and it also helps the student to keep concentrated during the instruction. The use of learning strategies can help the student to approach the learning of the new information in a better way, and can therefore enhance the learning experience. Finally, practicing the information triggers an active learning attitude, and opens the student to feedback on his practice. The feedback is needed to guide the student in the right direction based on his practice.

When the information is provided, the instruction needs to be concluded. To enhance remembering the content of the instruction, the student needs to be provided or to create a summary and a review of the important aspects of the instruction. The learning also needs to be transferred in order for the student to be able to apply the content outside of the instruction. Finally, the student is remotivated and the instruction is ceased.

After the instruction, the student can be assessed, so the instructor knows what the student has learned from the instruction. The instructor can also again provide feedback to take away misconceptions with the student.

<b>Expanded Events of Instruction</b>	
Generative	Supplantive
Introduction	
Activate attention to activity	Gain attention to learning activity
Establish purpose	Inform learner of purpose
Arouse interest and motivation	Stimulate learner's attention/motivation
Preview learning activity	Provide overview
Body	
Recall relevant prior knowledge	Stimulate or recall of prior knowledge
Process information and examples	Present information and examples
Focus attention	Gain and direct attention
Employ learning strategies	Guide or prompt use of learning strategies
Practice	Provide for and guide practice
Evaluate feedback	Provide feedback
Conclusion	
Summarize and review	Provide summary and review
Transfer learning	Enhance transfer
Remotivate and cease	Provide remotivation and closure
Assessment	
Assess learning	Conduct assessment
Evaluate feedback	Provide feedback and remediation

Table 2: The Expanded Events of Instruction by (Smith &amp; Ragan, 2005)

## Supplantive and Generative Instruction

As can be seen in table 2, each event can be performed in a generative way or a supplantive way. According to Smith and Ragan (2005), the choice between generative and supplantive strategies is a balance between a low and a high level of scaffolding. With a high level of scaffolding, the instructor is able to decide and define exactly how the events are used and how the content is delivered. The advantage of a high level of scaffolding is that misconceptions can be prevented, that the content is more connected to the learning objectives and that the learning task is easier to perform. However, the more supplantive an instruction is, the less active the learner has to be during the instruction. With a lower level of scaffolding, the student has to be active in order to learn the content and in order to decide what has to be learned from the instruction, which enhances the learning process.

Because the literature suggests the use of thought experiments and therefore also triggering reconsideration of the own models of students, critical thinking, an active learning style, extracting results and drawing conclusions as specified in design principles 6, 10, 7, and 8 on page 32, generative strategies have to be applied when providing the information to the students. This can be achieved by letting the students discover the mechanics behind the blocks introduced by qCraft for themselves. However, it is also important that the students receive proper feedback on their observations as specified in design principles 2, 3, 4, and 9, therefore scaffolding has to be provided during the feedback event. This can be achieved by providing feedback within books.

## Types of Learning

The final step before writing the framework itself is determining the type of learning of the instruction. Normally, only one type of learning forms the base for the whole instruction. However, because there is a variety of content domains, the decision was made to give each domain mentioned in the Topical Domains appendix (see page 82) an own type of learning, albeit that most domains fall within concept learning.

As the name might already suggest, the Preknowledge domain falls within the Declarative Knowledge type of learning. Declarative knowledge does not require the student to apply their knowledge but focuses only on memorising the content. This is also the case for the Preknowledge domain, for it only requires the student to memorise the order and structures of the atom. Furthermore, only focusing on the memorised facts is sufficient, for the student is presumed to already know these concepts and relations. The Applications of Quantum Mechanics is also only provided as declarative knowledge, for the applications are merely referenced and not further explained.

The elementary particle however is a new concept, and therefore understanding it falls within the intellectual skills, making this domain the type of concept learning. This entails not only learning the definition of the concept, but also learning to classify examples of the concept by using the definition or learning to differentiate between other concepts.

One might think that the behaviour of elementary particles, which is observation dependency, superposition and entanglement, might fall under principle learning, for the behaviour is something describing the objects and is not being an object itself. However, Smith and Ragan (2005) not only define objects as concepts, but also words such as "heat" or "up". The definition used before also applies to behaviour, for the student still has to learn how to classify certain behaviour or differentiate between different behaviours.

Realism and Ontology are considered to be concepts as well, for the student has to learn the difference between the two concepts and have to be able to classify certain statements as being realistic or ontological.

The uncertainty principle of Heisenberg however is a principle, as the name already suggests. It defines a relation between the concepts "uncertainty", "location", "momentum", "speed", "greater than or equal to", and "reduced Planck constant". These concepts do not need to be explained separately, for the student should already know them. An exception is the reduced Planck constant, however the

student only needs to know that it is a constant which has the value of  $1.0 \cdot 10^{-34}$ , and the concept of a constant should not be difficult for a physics student in upper secondary education. A principle should be comprehended by the student on a relation level, so the student should learn what happens to a variable if the value of the other variable would change. However, the student first needs to be aware of the meaning of the variables before learning the principle itself.

Finally, the teleportation experiment is taught at a procedural level, which means that the student should learn the steps of a procedure and how to perform the procedure.

## Framework

After assessing the different types of learning, the events of instruction had to be combined with the learning objectives in order to create the framework, which is displayed in the Initial Framework appendix on page 95. Within this framework, every separate concept got a separate sub-body, consisting of the events "Information and examples", "Focus attention", "Learning strategies", "Practice" and "Feedback". This was decided because of the variety of smaller domains and the different learning types of the domains. Because of the use of game-based learning, these events were not always presented in a certain order, for example "Practice" and "Feedback" in the Elementary Particles sub-body were combined together. Furthermore, the learning strategies were not regarded as an event, but as the incorporation of the design principles within the sub-body, since the game should already trigger the student to interact in a meaningful way with the content.

# Development

After the entire instruction was designed, it now had to be developed. Although most of the decisions were already made during the design phase, there were still some decisions left to be made for the translation of the framework into the game of Minecraft itself. This entails choices for the design for the rooms, tutorials, the main hall and the writing style of the texts. Furthermore, some problems were encountered during the development which needed workarounds.

# Translation into Minecraft

The environment of the instruction has to meet two requirements: it has to be pleasant for the student, and it has to distract the student as little as possible. This forces a balance for the environment, for what is regarded as pleasant is often not the least distracting. Two examples of this would be a cubic grey box or a room in a baroque styled chamber. The grey box offers no extraction but is often regarded to be boring, whereas the baroque styled chamber is often regarded as beautiful but has a lot of distracting ornaments.

Not distracting the student from the content of an instruction falls within the subject of cognitive load theory (Smith & Ragan, 2005). The cognitive load refers to the collection of constraints on the working memory of the student, and when these constraints overload the working memory this has a negative impact on the effectiveness of the instruction. The theory entails a couple of techniques which can be used to reduce the cognitive load:

- Off-loading
- Eliminating Redundancy
- Synchronising
- Pretraining
- Segmenting
- Weeding
- Signaling
- Aligning
- Individualising

Off-loading, eliminating redundancy, and synchronising only apply when providing the instruction both visually and auditory, which will not be realised for the prototype of the instruction. Pretraining is a training in the names and characteristics before the instruction, so the student already knows the names and does not need to memorise them. However, this instruction actually serves as a pretraining for later instruction on experiments relevant to quantum mechanics. Segmenting refers to the allowing of time in between different segments within the instruction, so the student is able to absorb the information of the previous segment. Weeding entails the elimination of unnecessary material in order to leave more room for the student to learn the relevant information. Signalling refers to the use of advance cues of how to process the information, so the student can actively focus on the more relevant information instead of the extraneous material. Aligning the text with correspondent graphics reduces visual scanning. Finally, individualising refers to providing the instruction in multiple forms so the content can be learned matching the aptitude of the student.

## Aesthetic design

The aesthetic design is required to be pleasant for the student, but it also requires to not distract the student from the learning content. Furthermore, aesthetic design can be used to set a tone activating the student into being inquisitive towards the environment.

The choice of the main blocks used in the aesthetic design is an important aspect for the aesthetics. The blocks chosen are displayed in figure 5. The Quartz block was chosen to be the main building block of the map. This block has a white appearance, which is a very neutral colour. However, its appearance is similar to the marble blocks used in classical temples, and it has a pleasant texture. Furthermore, the blocks have five specific variants, which are the normal Quartz Block, the Quartz Pillar, the Chiseled Quartz Blocks, the Quartz Slabs, and the Quartz Stairs. The white colour finally also creates a tone of sterility, similar to the tone of a laboratory. However, if the room were to be too sterile, the student might be insecure of experimenting within the room. Therefore, to provide some contrast with the Quartz Block, the Dark Wood Oak Plank was added. Finally, the room needs to be bright in order for the student to not be obstructed by shadows. Therefore, it was decided that there should be Glass windows and Redstone Lamps illuminating the room. The Redstone Lamps were to be powered by Redstone Blocks, which also add some colour to the room.

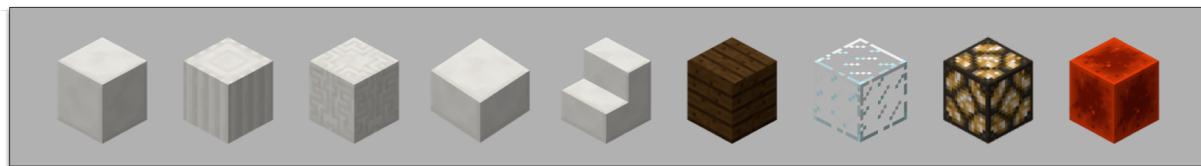


Figure 5: The main blocks used for the aesthetic design. In respective order these are Quartz Block, Quartz Pillar, Chiseled Quartz Block, Quartz Slab, Quartz Stairs, Dark Wood Oak Plank, Glass, Redstone Lamp, and Redstone Block.

After the choice of blocks, design choices for how to structure the blocks into a coherent formation have to be made. The first choice was to make use of repeating patterns and to make the room symmetrical. By doing this, the amount of unique features is decreased, because the existing designs are used more often, which reduces the need for more designs. This reduces the cognitive load as well, for the student has to process less unique designs. Furthermore, the features are separated by blocks coming out of the wall. By doing this, the student can easily discriminate between segments and it also gives the wall design some amount of depth. Finally, the design makes use of the golden ratio for the proportions between different segments. This makes the room more pleasant to look at (Livio, 2008). Because Minecraft exists out of blocks and the world only supports discrete distances, the golden ratio can be achieved by using only numbers from the Fibonacci sequence for the distances of the segments. The result of these aesthetic design choices is displayed in figure 6.

Because of the modularity and the multiple uses of the square room design, it is used throughout the map connected by short hallways. The only times the design is not used is when a larger room is needed. This is why there is also a bigger version of the room available, which is just an expansion of the original room design. By using the same design over and over again, the student gets used to the design and can therefore again focus more on the content of the instruction itself. Furthermore, by using multiple rooms, segmenting is used. This allows students to absorb the received information when moving to the next room.

## Sections of the Map

The instruction is delivered within a Minecraft map, which contains different sections. These sections are the incorporations of the different sub-bodies within the Initial Framework appendix (see page ??).



Figure 6: A screenshot of the design of an empty room, which is used throughout the instruction.

The map is custom-made in order to meet the needs stemming from the Initial Framework, and provides thereby a tailor-made solution.

## Tutorials

Because the instruction is delivered in Minecraft, the student first needs to learn how the avatar can be controlled. In order to teach the student the controls, a tutorial is included at the start before the events of instruction. This tutorial teaches the student on simple movement, jumping, how redstone works, how the messaging system works, how the inventory works and the use of items and books. Redstone is the term within Minecraft describing the logic component of the game. It involves signals from one block to another, how to interact with redstone with levers and buttons and what redstone can be used for, for example for opening iron doors.

The goal of the tutorials is to familiarise the student with the mechanics of the game, especially with the controls. Because it is not directly related to the achievement of the learning objectives, this has to be done as efficiently as possible. However, if too little attention is given to the student learning the controls, the student might not be able to get through the map at all. In order to keep the amount of text as low as possible, every instruction has been reduced to fit on signs, which allow only about 64 characters each. Another advantage of using signs is that the student does not need to switch between moving the character and having a book open, which decreases visual scanning and opening or closing the books. The signs are placed in such a way that the student reads it before he has to perform the action, which allows for signalling. Finally, the room is designed in such a way that the student needs to understand the controls in order to unlock the next room, which reduced the risk of the student not knowing what to do later. For example, the student needs to interact with the lever, button, pressure plate and tripwire hook system within the Interaction segment in order for the iron door to open.

After the student has learned how to operate within Minecraft, the actual instruction begins, starting off with the introduction. The first three events are delivered by a book. Although the attention of the student is already gained during the tutorial, the book still introduces the student to the world of Minecraft in order to direct the attention to the content. The writer also introduces himself as Professor qCraft. Furthermore, the professor establishes the purpose and arouses interest. After that, the student is

teleported to the main hall.

## The Main Hall

Between every segment, the student returns to a main hall. This is a room which connects all the different branches of the instruction. Every branch is labeled with a sign, so the student can get a preview on the instruction. Furthermore, every next branch has to be unlocked by completing the previous branch, and the first branch is already unlocked from the beginning. Having different parts of the instruction in different branches allows for more segmenting, for the student needs to spend time in between branches to walk to the next branch. Furthermore, because every branch is labeled, the student can already get a preview of the different branches. Finally, the student is provided a way of tracking his progress within the instruction.

In order to force the student to complete the branches in the order specified within the framework, the student has to unlock every next branch by completing the current branch. This is implemented by a ticket system. To unlock a branch, the student has to insert a ticket into a dropper at the end of the main hall. The dropper then sends the ticket into a system where the ticket is checked, opening the iron door corresponding to the ticket if the ticket is valid. A ticket can be obtained at the end of every branch. The ticket system has two extra bonus practicalities. The student has to spend even more time in between the branches allowing for more segmenting. The student also gets to see the name of the next branch when receiving his ticket, allowing for signalling.

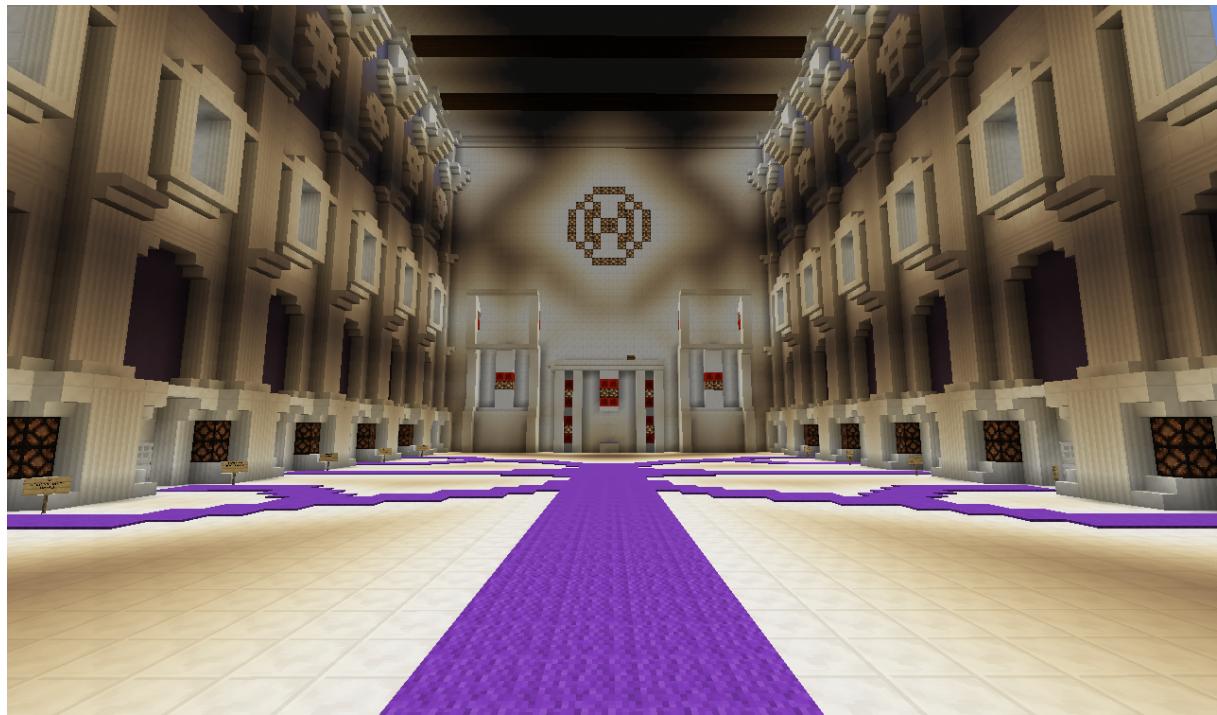


Figure 7: A screenshot of the design of the main hall.

The main hall is designed after the temple of Bacchus in Baalbek, and is displayed at figure 7. The entrances to the branches are located at both sides of the temple, and the dropper is located in an inner temple located in the centre of the back wall. Locating the dropper at the end allows for framing, directing the attention of the player. Placing the entrances at both sides is a natural placement, for there are already openings available at the sides of a temple.

As can be seen in the Initial Framework appendix on page 95, there are ten branches of the instruction accessible from the main hall. These branches correspond to the different topical domains specified on page 82.

## Rutherford-Bohr Model of the Atom

The body starts with the Rutherford-Bohr Model of the Atom. This is delivered via one book, and depicted by an illustration on the wall (the same picture as figure 8 on page 79). By providing the picture, the model is represented in multiple ways. The Rutherford-Bohr Model is included in order to activate the prior knowledge of the student, which is done according to the relating learning objectives. After activating the prior knowledge, the student will go through the series of small sub-bodies.

## Elementary Particles

The elementary particles is the first sub-body, which is introduced in the same book as the Rutherford-Bohr Model of the Atom, for these domains are closely related to each other. After the information is provided, the book states that the elementary particle is the most important concept of this book. After the deployment of information, the student can test whether he memorised everything by going through a multiple choice test. This test is a series of practice and feedback of declarative information.

## Theory of Relativity and Classical Communication

The Theory of Relativity and Classical Communication is also mostly delivered by book. There is also a contraption in the room visualising the concept of communication by two lamps with a signal connecting them, being activated once in a while. This books again starts out with prior knowledge, this time referring to knowledge about the Theory of Relativity. However, it could be the case that the particular student did not get any prior instruction about the theory of relativity, and because of this the information is provided in such a way that these students also still understand the information. After this information, new information is provided about classical communication. Thereafter the book focuses on the fact that classical communication is not instant, for this is relevant later within the Teleportation branch. Finally, the student is tested by having to calculate the time needed for a message to travel 1000 000 m, again providing practice and feedback of declarative knowledge.

## Discovery Branches

The following three sub-bodies are Observer Dependency, Quantum Blocks and Random Collapse, and Entanglement. These are the most important sections of the map, because in this section the qCraft blocks are used, and the student learns the most fundamental behaviours of elementary particles. First, the student is asked to discover the behaviour of the new block by comparing it to an already known block. The Observer Dependent Block is compared to a normal block, the Quantum Block to an Observer Dependent Block and the entangled Quantum Blocks are compared to two non entangled Quantum Blocks. By iteratively comparing a new block with an already known block, the student can link the new behaviour to already known behaviour. Furthermore, the student can focus on the important aspects of this instruction, namely the aspects of behaviour which are new. In order to find these aspects, the student has an active role in the instruction, he has to find his own results and draw his own conclusions, and has to be critical about his own conclusions. Furthermore, the blocks visualise the behaviour of elementary particles without the student needing a complex understanding of mathematics. At the end of the room an iron door is placed, which only opens when the blocks have collapsed to all possible states. By placing this door, the player is forced to first discover the blocks presented in the room before he can progress to the next room. After discovering the mechanic, a book explains what the student should have found, providing feedback, and then it transfers this behaviour to the context of elementary particles.

## qCraft Tutorial

After these sub-bodies, another tutorial follows, teaching the student how to use Quantum Goggles, Anti-Observation Goggles and the Automatic Observer. How the goggles can be used is taught by providing the student with the specific goggle and with a book containing information about the goggles. With

these items, the student can try the goggles for himself and confirm his ideas about these goggles by reading the book. The room is also scattered with Quantum Blocks, so the student can try to interact with these blocks while using the goggles. After the goggles, the student is confronted by a Quantum Resetter setup (see the Encountered Problems and Workarounds section below), in which he can try to find out how the contraption works. This is then again explained by a book, so the student can confirm his findings.

### Realism and Ontology, and Superposition

The next branch teaches the student about Realism and Ontology. By the means of a book, the student is first taught the questions researchers asked themselves upon finding the quantum phenomena. After that, the two interpretations are explained. The student is then asked which interpretation made more sense to him, triggering active and critical learning about different interpretations of the phenomena he witnessed earlier in the discovery branches. This is then followed by a small experiment, in which the student has to trigger a Quantum Resetter hooked up with a Quantum Block while wearing Anti-Observation Goggles, which causes the Quantum Block to remain in the state of superposition. This is then explained to the student in the book, and that this is an ontological interpretation. This emphasises the focus on the fact that quantum mechanics works in a probabilistic way instead of a deterministic way.

### Uncertainty Principle of Heisenberg

The ensuing branch presents the Uncertainty Principle of Heisenberg by using pictures on the wall, one picture displaying the entire principle and the other displaying the different variables used within the principle. The student is asked to investigate the pictures first, and then receives instruction about the principle. By having to explore the principle first, the student actively engages in trying to understand the principle. The instruction then serves as feedback on this understanding. The book then emphasises two implications following from the principle, which is the focus of this section. Furthermore, the student is asked what he would think the realistic and the ontological interpretation of this principle would be, which is followed by the answer. This way, the student actively engages in finding different interpretations of this principle, and is also able to connect the principle to the previous section. Finally, the student is taught about the scale in which the principle takes place, transferring the principle to the context of the real world.

### Quantum Teleportation

The final branch is the Quantum Teleportation experiment. In the first room, a simplified version of the entire experiment is displayed. The room also contains a chest with a book in it. First, the student is taught about science fiction teleportation and why this is not possible, which is included because this is likely to be the first association the student has with teleportation and has to be mentioned and rejected to make place for quantum teleportation. Then the book explains the different steps of quantum teleportation in order to give the student an idea of what is meant by quantum teleportation. After that, the student has to perform the teleportation in the next room from the perspective of the researcher in laboratory B, which provides procedural practice. The feedback is provided by an iron door at the end of the room, which only opens after the student has performed the procedure correctly. Finally, the student is asked whether quantum teleportation could be used for instantaneous communication, followed by the experiment of why this is not possible. By doing this, the student has to think in a critical way about the possibilities and the limitations of quantum teleportation.

### Conclusion

In the conclusion, the professor summarises the content of the instruction by using the teleportation experiment. By doing this, the student can review the different concepts he learned during the instruction

and connect them together. The professor also transfers learning by providing information describing where students could learn more about quantum mechanics, giving the students a preview for possible follow-up instruction. Finally, the professor closes the instruction.

The assessment events within the prototype are conducted using interviews.

## Text

The text had to be written in such a way that it was comfortable for the student to read, without including extraneous information which would only increase the cognitive load. Because of this, the resulting text is an almost direct translation of the learning objectives and standards. However, to make the text something into more than only an enumeration of learning objectives, a few story elements were added. One of these elements is the fact that the writer is an actual character which introduces himself as professor qCraft. The student even meets with this professor at the end of the instruction. This does not require a lot of cognitive load, because it requires only a few sentences. Still, it gives a more personal flavour to the text. Another story element is the fact that the professor is trapped in his office and that the student has to save him. This is added to give the student an external reason to go through the instruction and also added an element of gamification. The story however is reduced to only these two aspects. After the text was written, weeding was applied to the text in order to reduce the amount of information to only the necessary information.

# Encountered Problems and Workarounds

During the development of the instruction, two significant problems were found with Minecraft. The first problem was that the adventure mode did not entirely work the way it should work. The Automatic Observers of qCraft also worked differently than expected.

As stated before, the adventure game mode is supposed to prevent a player from breaking any block. In the version of Minecraft 1.7 however, it is still possible for the player to destroy some of the blocks. One would think that this problem could be simply solved by just avoiding these blocks. This is not always possible though, because some of these breakable blocks are quite significant. For example, redstone lamps, glass blocks and redstone lines are all breakable and are integral for the map to work. The problem was solved by placing all these blocks out of reach, and by telling the students beforehand that these blocks were breakable without the intention for them to be breakable. Another solution would be to use version 1.8 of Minecraft, for in this version it is not possible anymore to break any blocks in adventure mode. However, qCraft has not been developed for this version yet, so for now version 1.7 has to be used. On a side note, version 1.8 would be better in more aspects, for it has more possibilities for map makers. An example of this is the fact that with version 1.8 a new feature was introduced with the ability to place blocks by using commands.

The other problem was related to the Automatic Observers and their effect on Quantum Blocks. As explained before, if an Observer Dependent Block is observed, it collapses depending on the angle from which it is observed, and if a Quantum Block is observed, it collapses at random. However, when a Quantum Block is observed by an Automatic Observer, it behaves like an Observer Dependent Block, always collapsing the same way, dependent on the angle of the Automatic Observer. This is different behaviour than it would be expected, and closed off certain possibilities for the use of Automatic Observers. Fortunately, the main use of the Automatic Observer within the instruction was the fact that it resets the collapse of a qCraft block when the Observer gets deactivated, for this is used teaching the student about superposition. Therefore, the work around for this problem was to rename the Automatic Observer to Quantum Resetter, and making it so that if it is triggered, it would be activated and immediately deactivated, resulting in a reset of the state of the qCraft block.

Finally, the Quantum Goggles were also not behaving quite the way they were expected to work. Purely based on the description of the item, one would think that its function is only highlighting the blocks. However, the Goggles also work as Anti-Observation Goggles, and if a qCraft Block has an air block block type, the Goggles make that block into a physical block. This did not need a workaround within the current instruction.

# Formative Evaluation

At the stage of having fully developed a prototype of the instruction, it can be evaluated. Verloop and Lowyck (2009) enlists two types of evaluation, which are formative evaluation and summative evaluation. The main goal of conducting formative evaluation is to find areas of improvement within the instruction, whereas the main goal of summative evaluation is measuring whether the instruction is satisfactory within the achievement of the goal specified for the instruction. Within the generic model, the formative evaluation is displayed by the vertical bar on the right side, which conveys an interaction between the different development phases and the evaluation. Summative evaluation is displayed by the horizontal bar at the bottom of the model, which is conveyed to be an endpoint for the development of the instruction (see figure 1 on page 10). As can also be seen, summative evaluation can only take place after the full implementation of the instruction, therefore only a formative evaluation is conducted.

Nieveen et al. (2012) enlists five evaluation methods, as can be seen in the Evaluation Matchboard appendix on page 127. These are screening, focus group, walkthrough, micro-evaluation and try-out. A focus group evaluation has been conducted already during the analysis phase, described in the Focus Group Evaluation section on page 22. Furthermore, in the Task Analysis section on page 21 it was already specified that a screening would be conducted after the development of the product using the learning objectives, and within the Design Principle section on page 32 it was likewise specified that a screening would be conducted after the development of the product using the design principles. A walkthrough still had to be conducted in order to test the practicality of the instruction, which entailed mostly testing whether the map was functioning correctly. These evaluations were all carried out sequentially and did not produce any significant results, for it was just a test without any new information. The micro-evaluation however will be the main evaluation, because it will provide information about the actual practicality and the actual effectiveness. This evaluation will be elaborated within the following section. The try-out evaluation will not be possible, for it requires implementation of the instruction.

# Method for the Micro-Evaluation

## Research Approach

Because the instruction will be formatively evaluated and not a summatively, a qualitative approach was chosen over a quantitative approach. This choice was made because qualitative data embeds the results more in context, which makes it more valuable for determining how to alter the instruction. Quantitative data usually proves to be more useful for a summative evaluation, for it is more reliable and can be used to determine the accomplishment of concrete learning objectives. The evaluation will be conducted with individual respondents, which is in contrast with the recommendation for collaborative learning. However, for a first evaluation it is beneficial to limit the amount of variables, which would be increased by collaborative learning.

## Research Goal

Baarda, de Goede, and Teunissen (2009) state that before conducting qualitative research, first the goal of the research has to be formulated. Kirkpatrick (1983) lists four different steps of measuring the effectiveness of a training, which provides different types of goals for the evaluation. The enlisted steps are Reaction, Learning, Behaviour and Results. The Reaction step entails measuring how the instruction is received, for example which part of the instruction was perceived to be difficult. Within the Learning step, the amount of knowledge retained with the student is measured. This can be achieved by comparing statements of the student with the corresponding learning objective and standards, for example by comparing the statement "Atoms are made out of molecules" with learning objective 2 (see page 89). The next step, Behaviour, can be measuring by letting the student perform behaviour and comparing this with the expected or intended behaviour. In the context of this instruction this could be the performance of a student on a test on the subject matter. Finally, the Results refer to the accomplishment of the main goal of implementing the instruction, in the case of this instruction this would passing the Centraal Eindexamen, and could be measured by the amount of students passing the Centraal Eindexamen. For this prototype, it is only possible to measure the Reaction and the Learning step, for the Behaviour and Results steps require the instruction already being implemented within the intended context. In summary, the goal of this evaluation is to measure the reaction of the student on the instruction, and to measure what the student has learned from the instruction, aiming to improve the instruction.

## Theoretical Significance

Not only are the results of the evaluation relevant from a practical perspective, but also from a theoretical perspective. Measuring what the students learn from an instruction using a purely conceptual approach delivered by game-based learning has not been conducted before, and this might provide more insights in the misconceptions the students hold towards quantum mechanics and in the methods usable for teaching quantum mechanics.

## Ethical Admissibility

Baarda et al. (2009) lists a couple of requirements for the research to be ethical admissible. One of these requirements is that the respondents have to participate on a voluntary basis. This is already accomplished by not forcing people to cooperate. However, to make sure the respondents are aware of the fact that they participate voluntary, they are briefed before the instruction in that they are free to leave at any moment and that they do not need to do anything that they do not want to do. By performing the focus group evaluation with the expert, false representations of quantum mechanics are avoided, which is another requirement. Furthermore, the data acquired from the research have to be processed anonymously, which is accomplished by referring to each respondent only by using respondent numbers. These numbers will represent the day and the time of day the respondent participated in the research. Finally, there should not be any adverse effects for the respondents, which is guaranteed by the fact that the respondents have no direct involvement in the topic. They do not have to pass the quantum mechanics component of the Centraal Eindexamen themselves, for this is not yet implemented.

## Research Questions

The main goal of the evaluation is to gain information about the reaction and about the learning of the respondent, and therefore the research question is split up into two questions, which are "How does the respondent react to the instruction?" and "What are the conceptions of the respondents about quantum mechanics after the instruction?", formulated as specified by Baarda et al. (2009).

## Action Based Research

In order to enhance the evaluation of the instruction, the decision was made to conduct action based research. This entails not only measuring the reaction and learning, but also making them participate in the improvement of the product. These improvements would then also be implemented in order to enhance the instruction itself, and measuring the effects of the improvements. This way, a more incremental approach is used in enhancing the instruction.

## Respondents

The micro-evaluation would be evaluated optimally by using physics students from secondary education, for these are the final target demographic of the instruction. However, the schools approached for delivering respondents did not respond to the request, and therefore this was not possible, and another pool of respondents had to be addressed. Because of this, undergraduate students were used as respondents, for these are similar to the target demographic, both in attitudes as in preknowledge. The properties of these respondents also still aligns with the results from the learner analysis. The preknowledge had to be tested though, for it could be possible to vary from the preknowledge, especially considering technical undergraduate students. As such, a pretest was included in the evaluation. Using undergraduate students does have one advantage, namely that they are not involved with the education of quantum mechanics in any way, and therefore creating misconceptions with the students not familiar with quantum mechanics is not that harmful when compared it with creating misconceptions with secondary education physics student which still might need comprehension about quantum mechanics in their future lives. However, it would be beneficial to evaluate the instruction with the target demographic to gain more insights in its actual effectiveness.

## Concepts Central to the Research

Before the research can be conducted, it is important to enlist and define the topics central to the research, for these provide handholds during the data gathering process. As stated before, the evaluation measures the reaction and the learning of the student. The topics within the evaluation of the learning of the students are parallel to the content domains of the instruction as already defined in the task analysis

on page 18. These topics are Elementary Particles, Classical Communication, Observer Dependency, Realism and Ontology, Superposition, Entanglement, the Uncertainty Principle of Heisenberg and Teleportation. The applications of quantum mechanics are disregarded, for these do not contribute to the conceptual understanding of quantum mechanics.

However, for measuring the reaction, new topics are needed. As stated before in the Learner Analysis on page 17, some of the students might already have knowledge of quantum mechanics before the instruction. This influences the results, especially on a learning level. Therefore, the student has to be asked which content was new. Furthermore, the student might experience difficulties with controlling the avatar, with knowing what to do at all times and with the information presented within the game. Difficulty can stem from the language used within the books, but language encompasses more than only the difficulty of understanding it, for example the writing style or the tone used when delivering the text. Next to the text element of the instruction, there is also a gameplay element. These elements do not independent of each other, because a right balance is required between the amount of text and gameplay. Furthermore, learning about quantum mechanics could have a certain philosophical value, and can also have an amusement value. Finally, next to the importance of learning from the instruction, it would also be beneficial if the student would be motivated to learn more about quantum mechanics.

Hence, the topics are:

- Reaction
  - New information
  - Difficulty
  - Language
  - Use of Minecraft
  - Ratio between the amount of text and the amount of gameplay
  - Philosophical value
  - Amusement value
  - Excitement about quantum mechanics
- Learning
  - Elementary Particles
  - Classical Communication
  - Observer Dependency
  - Realism and Ontology
  - Superposition
  - Entanglement
  - the Uncertainty Principle of Heisenberg
  - Teleportation

## Methods of Data Gathering

There are different methods of data gathering available, which are document analysis, observation and interviews. Document analysis entails the study of already available material in order to learn something about the current setting of the topic. In the case of this instruction, data could be gathered by analysing other available teaching material or documents describing how to teach quantum mechanics. However, this aspect is already covered, both in what to teach from Zeilinger (2005) and as in the current experience with teaching by consulting the literature. An observation will be conducted, for the behaviour of the respondent during the instruction could provide insights in what areas of the instruction should be

improved, which is essentially the goal of the instruction. However, the main results will be provided by interviews, for by conducting interviews the student is able to voice opinions about the instruction. Furthermore, the student could even get involved by improving the map by being asked how it could be improved. Finally, the student can be tested on comprehension of the instruction. By using interviews instead of testing, the student can also explain the difficulties for thinking of the correct answer. Finally, the student can be helped if needed, so the understanding can be measured on a deeper and more thorough level. In contrast to a test, the interviews cannot be used to validate the instruction, this is however not the goal of a formative evaluation.

## Pretest

Before the observation and interviews could be conducted, the preknowledge of the respondent had to be measured. This pre-test would give valuable information for the analysis of the results. First of all, the age and the sex of the respondent were gathered, serving as descriptive data. Furthermore, the current study and the high school profile of the respondent were included in the pretest, providing technical background of the student. The high school profile is an aspect of secondary education in the Netherlands. In the upper half of secondary education, the student is allowed to choose between a profile containing non technical subjects or a profile containing technical subjects. To gain an idea of the knowledge the respondent already has about quantum mechanics, the respondent has to react to three concepts, which are quantum entanglement, the uncertainty principle of Heisenberg and superposition. Furthermore, the respondent was asked whether quantum mechanics is weird. Finally, the gaming experience of the respondent was determined by using a list containing the items Minecraft, first person games, third person games, mouse and keyboard games, console games, mobile games and no gaming experience.

## Observation

The purpose of the observation used for this evaluation is to observe the behaviour of the respondent, but also to get a direct reaction of the respondent to the different components of the instruction. The observation scheme contained different sections corresponding to the branches of the instruction. Within each section, there was a line to note the duration of completing this section and a text area for observation notes. The choice for its free form was made because the reaction of the respondents were hard to predict. Noting the time could provide to be useful for comparing the lengths of the different segments with each other, comparing the different students with each other and looking at the effect of the alterations between the different versions of the instruction. The role of the researcher was to interfere with the instruction as little as possible and thereby preventing observation-bias, but providing help when needed. The researcher also had to encourage a thinking out loud protocol with the respondent, for this allowed him to get a more visible reaction from the respondents.

## Interviews

Finally, the interviews are conducted. Because the interviews are conducted face to face and intended to let the interviewee provide reactions or understanding without obstruction, the interview would be open. However, to still have coherence between the interviews and to make sure the interviewee had to respond to all of the knowledge domains of quantum mechanics, a choice was made for a topic interview. The topics were already specified in the Concepts Central to the Research section. Furthermore, because the micro-evaluation is conducted with individual respondents, the interviews will also be held on an individual basis. This also has the advantage that the respondent feels more secure with regard to comprehension of the material, and with regard to the freedom of expression of opinions (Baarda et al., 2009).

For measuring the understanding of the respondent, associative and projective techniques were used. This was done by asking the respondent to tell everything about a certain concept, and when stuck the

interviewer would help. For example, if the respondent forgot the exact term for the light particle, the interviewer would help by saying "photon", and the respondent could continue explaining.

As stated in the previous section, the respondent would be briefed before the evaluation. Next to what is stated in the Ethical Admissibility section, the briefing also contained an introduction of what the respondent could expect from the instruction, and from the evaluation in general. Finally, the respondent was asked whether or not recording the interview was allowed.

Before heading into the topics, the respondent was asked an opening question, which was "Can you tell me something about your experience of the instruction?" This question was constructed to be very general, so the interview could begin with what the respondent thought to be most relevant, and thereby reducing the influence of the interviewer. This response could then be used for further questioning using the topics if possible. For example, if the respondent started with stating that the instruction contained a lot of information which had to be processed, the interviewer could ask what information was new, or whether the respondent found this to be difficult.

At the end of the reaction component of the interview, the respondent was asked for possible improvement areas for the instruction. This way, the respondent had a final chance of expressing his remaining thoughts. Then, the topics of the learning component were introduced one by one which the respondent was asked to make effort to explain. After all these topics had been discussed, the interview was concluded by thanking the respondent and if needed attributing possible feelings of guilt remaining with the respondent about the performance of the test to external factors. For example this could be done by attributing the performance to the fact that the instruction was still in development and still had to be improved. This was done in order to let the respondent leave with a good feeling about the experiment.

## Analysis of the results

In order to draw conclusions from the data gathered within the evaluation, the data needs to be analysed.

### Data Preparation

Before the data can be analysed, the data has to be prepared for analysis. Three tables were generated from the information gained from the pretest and observation. The first table contained the information of the pretest for each respondent. Furthermore, the time the respondents needed to complete the sections of the instruction were also included in a separate table. Finally, the notes from the observations schemes were organised by the respondent and the section. All interviews were transcribed.

### Coding the Transcriptions

The transcriptions of the interviews still needed to be summarised into coherent parts. This was achieved by labelling relevant fragments within the texts, as suggested by Baarda et al. (2009). The labels were derived from the concepts specified earlier on page 51. However, labels for statements regarding the suggestions for improvement still had to be added. The suggestions could be categorised into four labels: Improvements of the map, Improvements of the text, Improvements for qCraft, Improvements for Minecraft. Of these, only the first two could be implemented, however the other two categories were still noteworthy. By having the different statements of the interviewees labelled under these concepts, the interviews could be summarised in the results section. During the process of labelling, some more codes were found. These were the Learning Process of the Student, the Playing Experience of the Student, the Relevance of Learning Quantum Mechanics, and Criticism towards Quantum Mechanics. The fragments coded with the Learning Process of the Student related to every statement about this internal learning state. This entails how the information is processed and which parts were useful or irrelevant. Every fragment coded with the Playing Experience of the Student related to all the statements in which the respondent addressed the gameplay elements used throughout the map. Furthermore, the Relevance code is used for fragments stating the opinion of the respondent about the relevance of learning quantum mechanics. Finally, Criticism towards Quantum Mechanics entails asking critical questions towards

quantum mechanics or expressing epimistic doubt towards certain theories or interpretations. After the labelling had been finished, the fragments within the labels were ordered by the kind of statement within the fragment. This way it was possible to describe the different statements within the labels.

# Results of the Micro-Evaluation

This chapter describes the results from the pretest, from the observation and from the interviews. Furthermore, the results were used for rapid prototyping and for making a typology of the different kinds of respondents.

## Pretest

From the pretest, information was gathered about the age of the respondents, their sexes, their high school profile, and their knowledge of and attitudes towards quantum mechanics. A summary of the results of the pretest is displayed in table. There were 15 respondents in total, of which the average age was about 22. A distribution of their age can be found in figure 16 on page 130. The respondents contained a fair distribution between male and female students with 8 male and 7 female respondents. Furthermore, 10 of the respondents had a technical high school profile. Some of the respondents were international students from Germany, where there is no such thing as a technical high school profile as in the Netherlands. They however did not have had the same level of physics education and therefore they were labelled as not having a technical profile.

Number of respondents	15	
Average age	21.67	
	Male	Female
Sex	8	7
	Yes	No
Technical Profile	10	5
General knowledge	6	9
Entanglement	5	10
Uncertainty principle	4	11
Superposition	4	11
Weird	7	8

Table 3: Descriptive statistics displaying the results of the pretest

The distribution of the current studies are displayed in figure 17 on page 130. Within the respondents, there was one student studying Electrical Engineering (EL), one studying Educational Science and Technology (EST), three studying International Business Administration (IBA), two studying Industrial Design and Engineering (IDE), three studying Computer Science (INF), one studying Educational Science (OWK), and one studying Psychology (PSY). One respondent was a PhD student and one respondent was still a high school student in havo 5. This is thereafter summarised within chart 18 displaying in which faculties the students are enrolled, in which BMS is the faculty of Behavioural, Management and Social Sciences, EWI is the faculty of Electrical Engineering, Mathematics and Computer Science, and

CTW is the faculty of Engineering Technology. Else represents the high school student, and the PhD student is enrolled within EWI.

Six of the respondents had general knowledge about quantum mechanics, of which five respondents knew the concept of entanglement and four respondents knew the uncertainty principle of Heisenberg and the concept of superposition. These variables were incremental, for there was no one with a non technical profile who had some idea of quantum mechanics and in order to know a concept within quantum mechanics one had to know something about quantum mechanics in general. Seven respondents thought of quantum mechanics as being weird.

Finally, the gaming experience of the respondents is displayed within figure 19 on page 131. These categories are also incremental, they represent only the most relevant gaming experience of the respondent, so a respondent having played Minecraft also can have played First person games in general. One of the respondents already played Minecraft with the qCraft modification installed before, so this respondents already knew how the blocks introduced by qCraft worked on beforehand. Six of the respondents had already played Minecraft before, so these respondents already knew how to control the avatar within the game. Three respondents had at least played first person games, and two respondents had played third person games. These categories of games mostly share the same control schemes with Minecraft, so these respondents only needed to learn the features of Minecraft. The advantage of respondents with first person experience over respondents with only third person experience is the fact that these respondents were already used to the fact that Minecraft is also played in a first person perspective, which has more direct mouse controls than third person games. There were two respondents stating that they have only played mouse and keyboard games, so they also needed to still the general control scheme of three dimensional games. Finally, there was one respondent who stated to have no gaming experience, which means that this respondent also had to get used to game mechanics in general.

## Durations

The results from the observation yielded two types of data, which were the timestamps when each section was completed for each respondent and the notes made during the observations.

The timestamps first needed to be converted to the duration of each individual section for each respondent. After that, the average durations needed to complete the different sections were calculated, and are displayed in both table 4 and figure 20 on page 132. These averages give an idea about the length of each section and the total time the respondents needed for completing the instruction. As can be seen, these averages are split up in different versions, this is because of the alterations made during the rapid prototyping based on the results of the observations.

## Observations from Evaluating the Initial Instruction

In general, most respondents were positive about the instruction. One respondent even stated that it was a shame it was over. There were a couple of comments on the instruction however. Some respondents expected more gameplay elements like puzzles. Respondents also stated that the instruction could be boring, and some even stated that they thought it was boring, which could be partly due to the fact that all of the qCraft branches were placed in one cluster, and that the rest of the branches were heavily text-oriented. The rest of the comments applied on specific branches, and will be elaborated in the following sections. A note mentioning is that a reader could get the idea that the instruction was received very negatively, however, the observation focused itself mainly on aspects which could be improved, which yields more negative results. In order to get a good idea of the validity of the instruction, a summative evaluation would be required, making use of quantitative research methods.

Section	v1	Teleportation v2	v2
Tutorial 1	00:07:57		00:05:24
Microscopic World	00:06:10		00:06:10
Observer Dependency	00:04:35		00:08:31
Quantum Blocks	00:04:01		00:05:10
Realism and Ontology	00:05:42		00:03:19
Tutorial 2	00:06:09		
Superposition			00:04:04
Heisenberg	00:06:41		00:06:41
Classical Communication	00:04:30		00:04:27
Entanglement	00:05:27		00:08:53
Teleportation	00:08:01	00:17:31	
Conclusion	00:03:34		00:03:34
Total	01:02:48		00:56:13

Table 4: The average times noted in HH:MM:SS needed for each section in both the initial and the final version of the instruction, followed by the average time it took a student in total.

## Tutorial 1

Respondents with experience of playing Minecraft had of course no problems getting through the first tutorial. However, the respondents who did not have this experience encountered several problems. Some of the respondents had difficulties with controlling the character, these were especially those who did not have experience with playing third or first person games before. An example of this is that sometime the respondent had troubles getting through a door in order to progress to the next room. One respondent tried using the arrow keys and was confused that nothing happened, even when the sign indicating that the WASD keys should be used was on screen. However, most respondents had not much problems with the first person controls, which entailed looking around, moving and jumping. Sometimes the respondents would get disoriented. This could also be attributed to the fact that the rooms are symmetrical in design, so sometimes there were not enough handhelds for the direction of progress. This did not happen very often though.

The goal of a room was also not always clear, in this case the respondent asked the observer what to do next. This was especially apparent in the Signals room of the Redstone section, because the respondent only needed to see something and did not need to do anything, which was the case in previous rooms. Furthermore, if the respondents were told that they needed to look at the contraption in the room and learn from it, they still did not know what to look at, and after a while they just progressed. All of the respondents needed verbal instruction on how to use the books. Books are easy to use, but difficult to learn how to use, and no solution has been found yet other than giving verbal instruction. The difficulties with operating the game faded away very fast when the respondents got used to the controls, and the controls provided no problems for the rest of the map.

Some of the respondents complained that the long walk to the end of the hallway and back again to the entrance of the next branch was tedious and took too long. Also, the time needed for the dropper system to open the door took too long. Finally, the respondents did not always know where to go next because they were disoriented after walking to the end and back.

## Microscopic World

Most of the respondents recognised the Bohr model already from secondary education and did not experience many problems reading the book, only the havo 5 student did not recognise it. Therefore it is fair to assume that members of the target demographic do have the required preknowledge. Some of the students already actively tried to memorise the different facts from the book, which is logical considering that most of the content is declarative knowledge. Most of the respondents got through the test the first time, some of the respondents had trouble with the last test room. When confronted with not having memorised the required knowledge, the respondent would just reread the book. Some of the respondents did still know it, but wanted to verify their conception before entering the answer.

## Classical Communication

One of the first respondents suggested the use of Noteblocks to enhance the contraption. When a Noteblock receives an active signal, it makes a short sound. This could be used when a lamp would get activated. Some of the respondents did miss the question which asked them to calculate the time necessary for a particle to travel from one location to another, and some respondents missed the answer generated by the message system. Other respondents just did not feel like calculating and therefore just skipped the question. Most respondents answering the question did get the correct answer, although some of them needed pen and paper to do so.

## Observer Dependency

In all three of the qCraft branches, all of the respondents missed the request to find the difference between the two blocks presented in the room, which was again provided by the message system. The only priority of the respondents was opening the iron door. This could be achieved by walking and looking around, which after a while resulted in an open door without needing any comprehension of the behaviour of the blocks. Most respondents did find that the Observer Dependent Blocks occasionally change their appearance. Some of the respondents tried to jump on the blocks, because they could interact with the block that way. This behaviour could be extended for quite a while. In spite of all this, most respondents did comprehend the behaviour after reading the book, although some of them still needed some verbal instruction in order to understand it fully.

## Quantum Blocks

This branch suffered the same problems as the previous blocks, except that this time the respondents were more aware of the fact that they had to find the behaviour of the blocks in the rooms. Still, it seemed that at first the priority was opening the door, and only after that the respondents would try to find the new behaviour of the blocks. Some of the respondents missed the fact that the block displayed on the left was the same block as the one encountered in the previous room. Others tried to elaborate what behaviour determined to which state the right block would collapse this time, where this behaviour was random. This however did provide them with a better understanding of the realist dilemma. A couple of respondents started to anthropomorphise the Quantum Block, saying that it was purposefully tricking them.

## Entanglement

Within this branch, most respondents did find the behaviour before reading the book, and it thereby seemed to be more apparent, even when the respondents were only trying to open the door and not purposefully finding the specific behaviour.

## Tutorial 2

All of the respondents did not have any trouble finding the functionalities of both goggles. The quantum resetter was however found to be confusing, where it took a while before the respondents linked the pressing of the button with the observation effect. Some of the respondents tried the quantum resetter only with the newly acquired goggles without trying it not wearing any goggles, which was not the intention. Quite some respondents thereby already witnessed superposition, without understanding what they were witnessing. Most of the respondents needed verbal instruction to understand the quantum resetter.

### Realism and Ontology

Some of the respondents started this branch by actively trying to identify the portraits. Most students however disregarded the portraits and started reading directly. All of the respondents who already had general knowledge of quantum mechanics already adhered to the ontologist interpretation, and those without preknowledge adhered to the realist interpretation. This was already expected on beforehand.

Some of the respondents started to lose concentration at this point, and read over the questions asked within the book. They also started complaining about the amount of pages within the books. None of the students had problems with conducting the small experiment in the side room, a couple of students however did experience some difficulty relating the experiment with the theory in the book, and required verbal instruction.

### Uncertainty Principle of Heisenberg

Again, respondents complained about the book containing too many pages. However, this time around they admitted that it was not really possible to make it shorter. Furthermore, the respondents did indicate that it was relatively easy to make sense of the formula, and one student even related the  $\sigma$  to the standard deviation, which is a correct interpretation of the symbol.

### Teleportation

This branch was very confusing, even to the respondents who already had general knowledge about the teleportation experiment. Especially the first room was very unclear, because there were not enough descriptions of the various buttons and lamps. Only after reading the book the respondents could make a little bit of sense out of the contraption, but it was still difficult to comprehend. The next room was solved by again trying things at random until the iron door opened. The final book containing the question whether quantum teleportation would be possible could be understood by the respondents and was answered with the correct argumentation.

### Conclusion

The conclusion did not yield any further problems for the respondents. The only problems stated by the respondents was that the professor talked too fast and a bit too much. Some of the respondents did discover that it was possible to trade with the professor and to deal him damage by hitting him, and there were even a couple of respondents which killed the professor. This however did not impact the instruction.

### Rapid Prototyping

Rapid prototyping entails applying short improvement and evaluation cycles, in which the results of these evaluations are used to improve the map, enhancing the playing experience and improving the learning effectiveness. In this case, the improvements were committed in between the micro-evaluations.

The respondents are numbered, and the number contains information of the day and time the micro-evaluation took place. The first time slot occurred at 10:00 - 11:30, the second from 11:30 - 13:00, the third from 13:30 - 14:00, the fourth from 14:00-15:30, and the fifth from 15:30 - 17:00. For example, the micro-evaluation of respondent 205 took place on the second day of evaluation within the fifth time slot. There was a limited amount of time available for the improvements in between, and they were therefore mostly based on the filled in observation schemes and from what was remembered from the interviews. The finalised version of the instruction can be found within the Final Framework appendix on page ??.

## Minor Alterations

First of all, some minor alterations took place. Most of these entailed bug fixing - for example when a player is teleported to a slightly wrong location - or the fixing of spelling and grammatical errors within the books. There were also some minor alterations related to the content of the instruction.

After the evaluation with respondent 101, 204, and 205, the ticket system was altered. Instead having the dropper system at the end of the main hall, smaller dropper systems were placed next to the entrances of the branch. This resulted in the player having only to walk the distance to the next branch making it less tedious. Furthermore, lamps were placed at both sides of every entrance, which were activated the moment the ticket was inserted, making it easier for the player to find his way.

Then, after the evaluations with respondents 301, 304 and 305, some of the elements of the tutorial were removed. This entailed the removal of the entire signal room, the removal of the wooden pressure plate and the tripwire hook system within the interaction room, and the removal of the entire input blocks room. These elements were redundant for the rest of the map, and also only led to confusion of the respondents. Furthermore, weeding was applied to the Theory of Relativity branch by changing its name to Classical Communication and eliminating the theory of relativity element, for the only information necessary was that particles can not travel faster than light, without understanding why this is the case. The calculation of the time needed for a message given the distance was also made easier by using a distance of 3000 km instead of 1000 km, which resulted in a time of 0.01 s instead of 0.00333 s.

Furthermore, because it was found that respondents in general had problems reading the messages from the Message System, all Message System messages were changed into messages on signs between the evaluations with respondents 305 and 401.

Some of the respondents did complain about the monotony of the qCraft block branches and of the text heavy branches. Therefore, between respondent 502 and 603, most of the branches within the instruction were reorganised into a different order, alternating between qCraft block branches and text heavy branches.

Finally, also between respondent 502 and 603, the second tutorial which taught students about the goggles and the quantum resetter was removed, dividing its components over the other branches, providing the Quantum Goggles within the Observation Dependency branch, and providing instruction about the Quantum Resetter within the Quantum Block branch. This was done in order to give the student tools at an earlier point so they could for example identify which blocks in the room were special blocks.

The Anti-Observation Goggles were provided within a new branch, the Superposition branch. The aim of this new branch was to take the superposition lesson out of the Realism and Ontology branch, so this concept would get more segmented and thereby more highlighted. The branch first provided the student with the goggles, then it let him practice with the goggles, and finally the contraption previously displayed in the side room within the Realism and Ontology branch was presented in a separate room, enclosed with a book containing the text explaining superposition, also taken from the Realism and Ontology branch.

Finally, the speed at which the professor talks in the conclusion section was altered on request of a couple of students.

## Quantum Teleportation Experiment

The first iteration of the quantum teleportation branch only led to confusion with the respondents, even though these respondents already had already a quite advanced understanding of quantum mechanics before the instruction. Because of this, after respondents 101, 204, and 205, this branch was temporarily closed off for respondents 301, 304, and 305.

Between the evaluation of respondent 305 and 401, a complete new iteration of this branch was implemented, as can be seen in the framework for the second version of the quantum teleportation experiment on page 109. First of all, the large contraption in the first room was removed. Furthermore, this iteration splits the first book of the first iteration into four books. The first book describes science fiction teleportation, the second book explains the role of the researcher at laboratory A, and the third book explains the role of the researcher at laboratory B. This allows for more segmenting between the books. The player now also has to perform the steps of the second book, which has to be done in a newly implemented laboratory A. The tests whether the student can follow the procedure were an enhanced version of the test in the previous iteration, for both the newly implemented laboratory A and the already existing B. This time, it was more clear in which laboratory the student was supposed to be standing. Furthermore, the buttons and lamps were also better labeled. Finally, the student had to perform three successful teleportation in a row in order to open the iron door, so the student had to put more effort in just trying buttons until success, and therefore requiring a better comprehension of the procedure in order to progress.

In spite of these enhancements, the following respondents still had problems with understanding the procedure, even the respondent who performed relatively well within the other domains. The respondents did know the science fiction teleportation, but the quantum teleportation experiment only confused them. This is also partly due to the lengthy instruction needed to explain the experiment. Furthermore, some respondents had difficulties relating the previous learned concepts to the experiment. Therefore, the decision was made to remove the teleportation procedure and its most important components were transferred to the entanglement branch, as will be described in the following section.

## qCraft Block Branches

There were also a couple of alterations made to the qCraft block branches, which are the Observer Dependency branch, the Quantum Block branch and the Entanglement Branch.

## Discovery Rooms

The rooms where the student learns about the different qCraft blocks had a couple of changes. Because respondent 101, 204 and 205 were focusing on only opening the iron door instead of on discovering the behaviour of the block, a sign was placed at the beginning of the room, asking the student to find the differences between the two present blocks. The iron door was also removed, which resulted in more discovery and less trying to open the door. Furthermore, between respondent 305 and 401, the blocks were placed on separate pedestals in the middle of a gap located in the centre of the room. This forced the students to walk around the blocks, forcing observations from multiple angles. Furthermore, respondents reported having trouble finding the exact behaviour of the blocks because they needed a lot of observations in order to get a big enough sample size of behaviour. This was made easier by adding more blocks on each pedestal, which was also implemented between respondent 305 and 401. Finally, some of the respondents were mainly observing the blocks from the corners of the room, where with the Observer Dependent Blocks the behaviour was more consistent when observed from an orthogonal angle. By placing pillars in the four corners of the gap and thereby obscuring view of the blocks from the corners of the room, the following respondents were more inclined to observe the blocks from an orthogonal angle. A floor plan of this final room can be seen in the Floor Plans appendix in figure 11 on page 124.

## Puzzles

Between respondent 502 and 603, puzzles were added to the qCraft block branches. In order to solve the puzzles, the student should apply knowledge about the behaviour of the qCraft blocks in order to be able to progress to the next room. First of all, these puzzles were introduced in order to add more gameplay elements to the game, because some of the respondents were complaining about the fact that the entire gameplay mechanic of the map could be summarised as moving from book to book, without much interaction with the map. The puzzles could therefore also make the game more fun to play and motivate the student. By having to apply the knowledge, there was also a higher guarantee that the student had learned the behaviour of the blocks in more detail. This is also in line with the Practice learning event of instruction (see table 2 on page 35). The floor plans of the puzzles are included within the Floor Plan appendix on page 124.

The first puzzle is entailed in the Observer Dependency branch, displayed in figure 12. The goal is for the student to go through the iron door located at the west side of the room. The slightly textured white blocks are representing a glass wall, dividing the room roughly in two halves, and separating the Observer Dependent Block in the north west corner. This block collapses always to a red block, except when observed from the east when it becomes a blue block. When the block is red, the iron door is closed, and when the block is blue, the iron door is open. When discovering the room, the student will find the block changing to blue, but will mostly again trigger an observation from the south when walking to the door because of the way the glass walls are located. The student can solve this puzzle in three different ways: he can simply not look at the block when walking along the glass walls, he can continuously at the block in order to not trigger a new observation, or he can wear the Quantum Goggles which also do not trigger any observations. In the least, he has to understand the effect of Observation Dependency.

The second puzzle is entailed in the Quantum Block branch, displayed in figure 13. This time, the student needs to pass through two iron doors which are placed in glass walls. For each iron door there is a Quantum Block, which block type is dependent with the state of the door. Therefore, the student has to trigger observations on a block until it had the right block type corresponding to opening the related door, which he has to repeat for the other door as well. In the next room, there are four Quantum Blocks of which their block types are all interdependent with one door. The student needs to make all of the blocks collapse to the blue block type in order to open the door. This time however, the blocks are hooked up to a Quantum Resetter, which makes it easier for the student to trigger an observation.

Then, in the Superposition branch, the student is also required to solve a puzzle, displayed in figure 14. This room is divided by a vertical gap reaching from west to east, which the students needs to cross in order to solve the puzzle. This can be done by walking over a bridge crossing the gap. However, the bridge consists out of Quantum Blocks, which can randomly collapse to the gravel block type. A feature of this block type is that it falls down. This makes random blocks making up the bridge fall down on observation. Furthermore, the bridge is build in such a way that it is hard to cross it without observing the bridge, and it is also hard to cross the bridge while looking continuously at all the blocks. The way this puzzle has to be solved is by wearing the Anti-Observation Goggles, which do not cause any observations on the Quantum Blocks and hence preventing them from falling down.

The final puzzle presented to the student is entailed within the Entanglement branch. This room is again divided by a gap reaching from west to east which the student needs to cross in order to progress. This time, there is a bridge crossing the gap made out of Quantum Blocks of which the block type can collapse to either the air block type or the quartz block type. There are also two walls consisting out of these Quantum Blocks, one at the beginning of the room and one at the end of the room. Furthermore, all these Quantum Blocks are entangled with each other, so they always collapse to an equal state. This puzzle can be solved by first making the block types of all Quantum Blocks collapse to air blocks in order to pass through the first wall, then altering the state to quartz blocks in order to cross the bridge, and then altering the state again in order to pass through the second wall. Alternatively, the block types of the Quantum Blocks can be collapsed to the air block type the whole time, and Quantum Goggles can be worn in order to cross the bridge. This is not an intended solution, however it cannot be circumvented. It is not that much of a problem, because the student probably still learns about entanglement.

## Book Alterations

Together with the implementation of the puzzles, the text within the books of the first iteration was split up and divided over multiple books provided between the gameplay segments. The books could be roughly divided into three categories: block behaviour, tools and transfer. The first books within the branch usually provided feedback on the discovery of the block behaviour by the student. This described purely the behaviour of the block which the student should have found, without referring to its translation of the real world. This is done in the Observer Dependency branch, the Quantum Blocks branch and the Entanglement branch. After that, usually a tool was introduced. These were the Quantum Goggles within the Observer Dependency branch, the Quantum Resetter within the Quantum Blocks branch and the Anti-Observation Goggles within the Superposition branch. Because of this, a book was needed to explain the use of these tools. Finally, a book was provided explaining the just learned behaviour in relation to the behaviour of elementary particles in order for the students to transfer the information to the context of the real world. By using different books for different categories, the text is more segmented, allowing for more time to absorb the information and for providing structure to the student, allowing for signalling of what type of information is contained within the book.

## Incorporation of the Teleportation branch

Finally, the elements of the Teleportations branch still needed to be incorporated within the other branches. This was done by putting the relevant elements into the Entanglement branch. The two laboratories were placed after the puzzle, and the books with instructions were rewritten to the context of applying the knowledge of bosons and fermions, instead of the context of the teleportation experiment. This way the knowledge of the student about bosons and fermions were still tested without the need for explaining the teleportation experiment. Lastly, the question at the end of the Teleportation branch was also incorporated at the end of the Entanglement branch, but was formulated in terms of possibilities of using entanglement for instantaneous communication, without any reference to the teleportation experiment.

## Observations from Evaluating the Final Instruction

After these changes, the respondents were more positive about the instruction. The speed with which the respondents went through the instruction increased as well, mainly because the block discovery process was made easier. The puzzles were also received positively, there was only one respondent who did not think of the puzzles as having an added value. The puzzles were also considered to be relatively easy. Finally, the students had less trouble with the parts stemming from the teleportation branch, in spite of them still having to do the same task.

## Interviews

In table 7 on page 134 the amount of fragments corresponding to the codes and to the interview. The codes in bold types within the vertical axis represent code families, and the bold type three letter codes within the horizontal axis represent interview families which will be elaborated in the Typology section. The total amount of coded fragments amounts to 830. There are only 14 interviews included in the table, for respondent 303 did not want to be recorded, hence there is no interview transcription for this respondent. The next couple of subsections will contain a description of the fragments corresponding to a specific code. To reiterate, this is a qualitative research and not a quantitative research. This means that the fragments within the reaction family only gives an overview of the different possible reactions and cannot be used for passing a certain judgement on the instruction. Furthermore, the fragments within the learning family only describes the different conceptions that students could hold on quantum mechanics after the instruction, it cannot be used to validate the instruction as being effective. The assessment of the instruction requires further quantitative research with members of the target demographic.

## Reaction

### New Information and Preknowledge

Many respondents stated that there was a lot of new information. Some stated that there was too much information to process. Most respondents already knew at least the atom model of Bohr, and some of them already knew relativity theory. Some of the respondents stated to already know the uncertainty principle of Heisenberg, and others have stated it to be partly known. For example members of this group already knew the principle of complementarity, but did not know the formula. The respondents which knew more about quantum mechanics stated that they were already familiar with the concept of entanglement, but that the concept of bosons and fermions was still new for them. One respondent already knew the fact that entanglement could not be used for communication, but did not know the quantum teleportation procedure.

### Difficulty

Some of the respondents thought of the map in general as easy or do-able, and also about the content taught within the instruction. One respondent even complained it was too easy and that he learned very little in too much time. Other respondents however stated the map to be difficult. To many of the respondents it was clear what they had to do, although some of the respondents had more trouble with finding the goal. As stated before, some students had no difficulty controlling the game, whereas other students needed more time to learn this. This duality was also expressed during the different interviews. Most of the respondents thought of the puzzles as being easy, where some of them expressed some difficulties in the beginning of some puzzles. The teleportation experiments were mostly experienced as being difficult. Some of the respondents had trouble with understanding the contraption, whereas others had difficulties comprehending the instructions. Many respondents commented on the message system being easy to miss. Finally, one respondent commented on the calculating within the Classical Communication branch being difficult, which was also found during the observation.

### Language

Almost all respondents did not have difficulty with the language or the writing style used within the books. One of the respondents stated that the writing style was a bit on the formal side, where one other respondent thought it to be just formal enough to not be street language. This difference could be explained by the fact that the text has changed during of the micro-evaluations. Some of the respondents stated having difficulties with having to read a lot of new scientific terms. Finally, only one respondent had difficulties reading the text in the English languages, for it was difficult to translating certain English scientific terms to the corresponding Dutch term. However, the rest of the respondents did not experience any problems with the English language.

### Use of Minecraft

Most of the respondents regarded Minecraft and the gamification elements as added values for the instruction, in which the respondents referred to the exploration, the immersion and the means of visualisation and interaction within the game. However, some of the respondents stated that just reading a book would also have worked. There were also respondents who thought that Minecraft could be used in an even better way, for example by adding puzzles or secrets in the case of the earlier respondents. However, after the puzzles were added, one other respondent did not see puzzles in general as an added value. Furthermore, one respondent complained about the graphics of the game, but all other respondents did not mind the graphics. A lot of respondents also stated the qCraft blocks as having an added value. Finally, a couple of respondents also commended other games, although they admitted Minecraft to be relatively easy to use.

### Amount of Text and Gameplay

The most heard complaint from the evaluations was that there was the amount of text being too high and the amount of gameplay being relatively low. This was especially the case within the Uncertainty Principle of Heisenberg branch, within the second version of the Teleportation branch and within the Conclusion branch. Other students expressed that the ratio was actually in balance, and one respondent even commented that further reading was still necessary.

### Philosophical Value

Almost all of the respondents could appreciate the philosophical value introduced with the two interpretations of quantum mechanics, although some of the respondents perceived it more to be a section describing the history of quantum mechanics than as a philosophical section. The respondents especially appreciated the fact that they were triggered to think about these interpretations themselves by evaluating which one would make more sense. Only one of the respondents commented it not necessary to be included, however this respondent was already a ontologist. This respondent also recommended the alternative of using other interpretations such as the Copenhagen interpretation and the Multiverse interpretation.

### Amusement Value

Most of the respondents regarded the instruction not only as being educational, but also as being amusing. An often heard reason for this was the fact that the instruction provided to be a nice introduction for a complex and difficult topic, without it being too difficult and while playing a game. Other specific aspects mentioned in this context were the gadgets provided by qCraft, the philosophical part, gameplay elements such as the ticket system, being challenged by the game, and the puzzles. Other respondents however thought it not to be very fun, and that it was obviously an educational game.

### Topical Excitement

When asked whether the respondent was more excited about learning about quantum mechanics, most of them affirmed this. Mainly this was because they now had an idea of quantum mechanics and that they now had an entrance. Some of them however stated that they were not more excited, but that they were going to be excited to begin with. When asked whether other people could get more excited by playing the instruction, most of the respondents answered that this would only be the case if they already were interested in it to begin with, and that people not being interested would also not be more excited. However, they stated that at least this instruction could trigger a certain curiosity. When asked to compare this instruction with traditional instruction, most of the respondent did think that this had a higher chance of attracting people their curiosity.

### Learning Process

In general, respondents had the idea that the content was explained well and that they have learned from the instruction. The parts the respondents mentioned as being useful were the discovery of the behaviour of the different qCraft blocks, the debate between realism and ontology and the question which interpretation the respondents adhered to, the verbal instruction provided by the observer and certain aspects of instructional design such as the activation of preknowledge, the checks at the end of the Elementary Principle branch, the overview at the beginning, the use of visuals and the conceptual approach instead of a mathematica approach. Another respondent however did not see why the debate between realism and ontology was relevant. Furthermore, respondents employed different learning strategies, like thinking of a bison to remember the boson concept, linking a theory to its inventor, rereading some of the books. One respondent expressed the need of making notes in order to remember every concept.

## Playing Experience

Respondents had different experiences from playing the game. Some respondents expressed positive aspects of their experience, such as the nice design and the way of tracking progress. Negative experiences were that there was too much reading, frustrations with controlling the character, or the slow progression. Some of these frustrations came from certain expectations, which was mainly the expectation of more gameplay elements like puzzles. The respondents also employed multiple playing strategies, of which the more remarkable strategies are enlisted here. Some of the respondents just tried random things until the door would open and they could progress. They stated that afterwards they did not learn anything by using this strategy, but that it was the most efficient strategy. Other respondents tried to look for secrets, comparing it with other puzzle games. Sometimes the respondent would skip a section in order to get through faster, for example the calculation in the Classical Communication branch. Certain respondents did not always know what to do.

## Relevance

Two respondents made a statement about the relevance of learning quantum mechanics, of which one stated it to be too far removed from the daily experience and thereby regarded to be not very relevant, whereas the other respondent thought of it as very relevant because it contributed to a fundamental and crucial understanding of science and thereby the world. Both of these respondents did have a low amount of preknowledge of quantum mechanics.

## Criticism towards Quantum Mechanics

Finally, some of the respondents expressed criticism towards the learning content. They asked themselves why the ontologist interpretation was more adhered by scientists, asked hypothetical questions which challenged the books or wanted to investigate the evidence for certain theories or interpretations.

## Learning

### Elementary Particle

When asked about the elementary particle, most respondents first enlisted the photon, electron and quark. Often, this was presented as the entire list of elementary particles. Sometimes, a respondent would have trouble with finding specific terms, like the term quark. Furthermore, most of the respondents could state that the elementary parts are the smallest particles or the basic particles. Some of the respondents could relate elementary particles to quantum behaviour or to the behaviour of the blocks. Sometimes, a respondent would relate them to the Bohr model. A couple of respondents mentioned some of the properties when asking to explain elementary particles, such as charge. Finally, there were a couple of respondents who were not able to explain the concept of the elementary particle at all.

### Relativity Theory and Classical Communication

Classical communication was often explained in terms of information theory "with ones ad zeroes". Furthermore, respondents stated that particles were needed, such as photons. Some of the respondents also stated that the particles needed to go through a communication channel. Most of the respondents stated that communication was limited by the light speed, sometimes recalling the exact speed. Finally, a couple of respondents mentioned the Theory of Relativity.

### Observer Dependency and Superposition

Observer dependency proved to a bit more difficult for the respondents. Some respondents were able to explain that elementary particles were dependent on observation, and when they would be observed they would collapse to a random state. However, observer dependency was sometimes confused with the

behaviour of the Observer Dependent Block, namely that the elementary particle was dependent on the angle of observation. Other respondents could not remember the term observer dependency at all. Quite a couple of respondents was still able to explain superposition as the elementary particle being in all states as the same time. Sometimes this was phrased as a "in-between phase" of the block state. These students could also state that this was the state of the particle before observation.

### Realism and Ontology

When asked about how to interpret quantum mechanics, the respondents could still enlist both the realist interpretation and the ontologist interpretation. Most of the respondents formulated the realist interpretation in terms of measurement, for example "there is something that we cannot measure by which quantum mechanics happen". Others would formulate it in terms of an underlying explanation, as in "there is something which explains quantum mechanics, we only do not know what that is." Some of the respondents could also explain ontology, which was often phrased something fundamental without an underlying explanation. A couple of respondents added to this that ontologist are "on the winning side".

Some of the respondents did not know how to explain realism or ontology at all.

### Entanglement

Only a few respondents could not explain the concept of entanglement. Entanglement was often explained in terms of interdependency or patterns. Most of the respondents also could still explain the concepts of bosons and fermions, where bosons were explained as "doing the same" and fermions as "doing something different" or "doing the opposite". Sometimes, these concepts were explained in terms of concrete block colours. No respondent has mixed bosons and fermions up. One respondent could still explain bosons and fermions, but could not generalise this to the concept of entanglement.

### The Uncertainty Principle of Heisenberg

Upon the question to explain the uncertainty principle of Heisenberg, a couple of respondents started with recalling the entire formula. Furthermore, most respondents could still state that one of the uncertainties could not be zero, and that if one of the uncertainties would become smaller, the other had to become greater. Some of the respondents did not get further than stating some of the variables within the formula, and some of the respondents got confused, for example by stating "if you want to know the speed of a particle, you have to know its location", taking out the uncertainty aspect.

### Teleportation

When asked about teleportation, a couple of respondents started with the procedure of science fiction teleportation. Sometimes the respondent got this type of teleportation mixed up with quantum teleportation, stating something such as "I do not understand how information can be sent by this." One of the respondents stated that teleportation was not possible, because the blocks change all the time. The respondents could tell something about what they did during the experiment, namely determining whether two blocks were bosons or fermions, and determining the colour of a block in another location. However, they were not able to explain the procedure of quantum teleportation itself. Furthermore, some of the respondents were able to give arguments why instantaneous communication was not possible. A few were able to state that the entanglement had to be measured and this needed both particles to be on one location, and somewhat more respondents could state that the collapsing of an elementary particle could not be influenced.

## Suggestions for improvement

### Improvement of the Map

Two of the suggestions were related to the order of the different elements within the instruction. One of these suggestions was to introduce the player to the goggles and quantum resetter at an earlier moment in order to make them more useful, and the other was to mix the different sections up to make the instruction less monotonous. Another suggestion was to place more blocks of each type in the qCraft block discovery rooms, so the pattern of the behaviour would become more apparent to the player. It was also suggested to add some sound effects, such as the Noteblocks in the Classical Communication branch and the sounds of the professor in the Conclusion branch. The message system was also suggested to be entirely replaced by signs, for these were better visible. A large amount of suggestions referred to the addition of puzzles, which were incorporated into the puzzles within the final version of the instruction.

Other suggestions were related to the design of the rooms. One of these suggestions was to place lamps next to the entrances of the branches, so the player could find the next branch easier. The ticket system should also be faster, and it should not be necessary to walk all the way to the end every time in between branches. Furthermore, the books should be split up more. There was also a suggestion to alter the design of the Uncertainty Principle of Heisenberg branch, which was to make it more museum like with separate exhibitions for each variable.

Regarding the instruction, it was suggested to inform the player better about the purpose of the different rooms, such as finding the specific behaviour of the blocks in the discovery rooms. Another suggestion was to place some of the books containing extra background information behind optional puzzles, so the player would have extra incentive to read the book. One of the other suggestions was to put more checks inside the instruction, where the player is forced to apply his knowledge.

### Improvement of the Text

There were a couple of suggestions with regard to omitting some of the text. The main point was to reduce the amount of text, and one of the concrete suggestions was to omit the realism and ontology branch. Furthermore, some of the respondents wanted to translate some of the text to learning by doing something instead of reading. There were also some suggestions regarding to adding text, these were adding other interpretations of quantum mechanics, including the whole standard model of elementary particles, more repetition of concepts, and more demonstration of how "weird" quantum mechanics is, for example with the double-slit experiment.

### Improvement of qCraft

There were two suggestions for the improvement of qCraft. The first one was to make Automatic Observers operate correctly on Quantum Blocks, and the second one was adding fermion entanglement to qCraft.

### Improvement of Minecraft

All the suggestions for Minecraft boil down to the fact that Minecraft version 1.7 still had to be used instead of being able of using version 1.8. The latter has a proper adventure mode, which means that no block can be destroyed. Furthermore, some extra commands were added in 1.8, for example being able to place blocks using commands, and giving the player placeable blocks or tools with the ability of destroying certain blocks. These features give the map maker more possibilities for room design and puzzle creation.

## Typology

Finally, with the results of the pretest, observations and interviews, three distinct dimensions were found. One dimension is the preknowledge dimension, which entails whether or not the student has any preknowledge of quantum mechanics. The second dimension is the enthusiasm dimension, which embodies whether the student has an enthusiastic or a critical attitude towards the instruction. The final dimension is the performance dimension, which encompasses how well the student performs on the test about quantum mechanics. With these three,  $2^3 = 8$  different typologies can be made. A typology is a categorisation describing a certain type of respondents. In table 5 the amount of respondents within each typology are displayed. In table 7 on page 134 the different typologies are indicated by a three letter code. The first letter refers to the preknowledge (P = preknowledge, N = no preknowledge), the second letter refers to the enthusiasm E = enthusiastic, C= critical, and the final letter refers to the performance (H = high performance, L = low performance).

	Critical	Enthusiastic-high	Enthusiastic-low
No preknowledge	3	5	2
Preknowledge	3	2	

Table 5: A display of the amount of participants within the different typologies.

There was no respondent with a high level of preknowledge and a low test performance, which is logical, because if the student already has a high level of preknowledge, a high test performance is expected. Furthermore, there was no student within the NCH category, so enthusiasm could be a requirement for a high test level. However, there are some students within the NEL category, so enthusiasm might not automatically mean a high test performance. This together results in only 5 remaining typologies.

Of course, it has to be noted that these dimensions are not as binary as represented in the table, but they would be more gradual and continuous. However, the typologies might still give some indication of the type of students. Furthermore, how often students fall within certain typologies still needs to be verified by quantitative research methods.

The respondents within the NCL category already indicated in the beginning of the instruction that they were not very interested in learning about quantum mechanics, and that they thought the instruction was boring. In two cases, the respondents did not have a technical profile and were not enrolled in a technical study. It is highly likely that the low performance on the test of these students is caused by a lack of interest towards learning quantum mechanics. Interesting enough, the other student did have a technical profile and was also enrolled in a technical study. This respondent was mainly critical towards the instruction and not necessarily towards the learning content, and this respondent indicated even that the instruction was too easy and that he could have learned it faster with traditional textbook instruction. It therefore might be the case that this respondent was underestimating the difficulty of the content and therefore performed low on the test. These students also highly doubted that secondary education students would benefit from this instruction.

Respondents within the NEH category had a positive attitude towards the instruction and maintained this attitude throughout the instruction. They also employed an active learning style by trying to memorise the content and asked critical questions about quantum mechanics during the instruction and the interviews. Because of this, they were able to perform on a relatively high level within the learning step of the evaluation. Within the reaction step, they wondered why or had wished that other instruction employed within secondary education could not be more like this, especially those with a non technical profile within this typology. Despite of their enthusiasm, they had still doubts whether students enrolled within secondary education would benefit of this instruction, and that this depended of their general attitude towards learning quantum mechanics.

There were also a couple of respondents who did have a positive attitude throughout the instruction but still performed on a low level during the learning step of the evaluation. One explanation could be that they were only giving socially acceptable answers because they did not want to hurt the instructor.

The other explanation could be that these respondents were not able to make their knowledge explicit due to the nature of how the topics were presented, although the interviewer has made an effort into giving the respondents cues to help get past this. Of course, there was a lot of information to process as well, especially considered that the respondents within this category were not enrolled in a technical study and therefore it has been a while since they had to learn something about physics for the last time. Within the reaction step of the evaluation, these respondents expected that secondary education students would probably benefit from this instruction.

There were also a couple of respondents with preknowledge of quantum mechanics which had a critical attitude towards the instruction. These respondents also had experience with building in Minecraft and could therefore already had expectations of the map on beforehand. This was especially apparent with one of the respondents, who stated over and over again that there were not enough puzzles within the instruction. This respondent also tried to go through the instruction as fast as possible, for he already knew how qCraft worked and was mainly looking for puzzles to solve. The other respondents were also stating that the map could make more use out of the gameplay features of Minecraft, albeit in a lesser extend. One of these respondents did partake with one of the micro-evaluations after the puzzles had been implemented, but still expected more gameplay and less text from the map. Because of their critical attitude, they doubted whether the instruction would be beneficial for students enrolled within secondary education.

Finally, there were a couple of respondents with preknowledge of quantum mechanics having a positive attitude towards the instruction. They stated that although already have read about the concepts, they still learned from the visualisation of quantum mechanics displayed by the various blocks introduced with qCraft. These respondents did also not mind the amount of text, for they were already pretty satisfied with text-only explanations. These respondents also had high expectations of students enrolled within secondary education for benefiting from this instruction.

## Conclusion and Discussion

Although the instruction still needs to be tested on validity and effectiveness by quantitative research, it is already safe to say that there is potential within the instruction. The results indicate that some of the respondents have formed a better conceptual understanding of quantum mechanics, and that some of the respondents are more motivated to learn more about quantum mechanics. Furthermore, Minecraft and qCraft were generally perceived as adding both instructional and amusement value. Finally, the instruction has shown to improve over the course of using rapid prototyping.

For the development of the instruction, a highly technical-instrumental approach was employed in order to include both instructional theories and suggestions from literature about teaching quantum mechanics. First of all, the generic model was used to structure the process, which started with the analysis phase. Within this first phase, the context, learner and task was analysed. This entailed a needs assessment of teaching quantum mechanics, a description of the learning environment, a description of the conceptions students generally hold about quantum mechanics, and a formulation a main goal for the instruction, of learning objectives and standards for these learning objectives. With the results of the analysis phase, a general design was made for the instruction. This encompassed the choice for using qCraft, the formulation of specific design principles displaying the suggestions from earlier research on teaching quantum mechanics and the development of an initial framework for the instruction in which the learning objectives were structured according to the events of instruction. With this framework, the instruction itself was developed. Within the development, there were still some choices left to be made, for which mainly a creative approach was used.

Generally speaking, the initial framework contained a tutorial for learning how to control Minecraft, a short introduction, the activation of preknowledge with the Rutherford-Bohr model of the Atom, the concepts of elementary particles, classical communication, observer dependency, random collapse, entanglement, realism and ontology, and superposition, followed by the uncertainty principle of Heisenberg, the quantum teleportation procedure and a conclusion of the instruction.

After the instruction was developed, it was formatively evaluated in order to improve the instruction and adjust the playing experience to the respondents. The main part of this evaluation consisted out of the micro-evaluations, in which respondents would individually go through the instruction. The respondents were first pretested before the instruction, observed during the instruction, and interviewed afterwards to measure their reaction and what they learned from the instruction. The results were directly used for rapid prototyping in order to improve the instruction in between the micro-evaluations, and to gain information about the strengths and weaknesses of the instruction. Finally, five different typologies were constructed in order to display the different kinds of respondents.

The observations and interviews yielded a lot of useful information for improving the map. Because of this, the branches got a new order, the quantum teleportation experiment was revised heavily, after which it got scratched from the instruction and largely incorporated within the entanglement branch, the qCraft block discovery rooms were altered, puzzles were added, and the books were slimmed down and split up over multiple rooms.

The instruction contained a lot of new information for those without general preknowledge of quantum mechanics. Its difficulty varied in the perception of different respondents, also within the group without preknowledge. The language and writing style within the books was perceived mostly as satisfactory. Most respondents thought of Minecraft and qCraft as an added value. In general, respondents indicated the amount of text was too high. The philosophical value triggered most respondents into having an active learning style and critical thinking. Furthermore, the instruction was mostly regarded to have an amusement value, although this was debated. Many of the respondents have gotten more excited about learning quantum mechanics, although some of them doubted whether students within secondary education also would get more excited. The respondents used varied learning processes during the instruction, and got varied experiences from playing. Some of the respondents stated something about the relevance of learning quantum mechanics, both stating it to be relevant as irrelevant. Finally, some of the respondents asked critical questions about quantum mechanics.

Most of the time, when asked about certain topics, a respondent would either be able to state correct conceptions, or the concept would simply have been forgotten. The only big misconceptions arose

from confusing the similarly named qCraft block with the actual behaviour of an elementary particle. This was most apparent in the case of observer dependency and Observer Dependent Blocks, where the respondent would sometimes state that the elementary particle is dependent of the angle of observation. This would suggest that maybe the Observer Dependent Block should not be used during the instruction. Furthermore, the teleportation experiment mainly led to the confusion of the respondent, hence it was scratched from the instruction.

Finally, some of the respondents made suggestion for improvement of the map and of the text within the instruction. These were mostly already incorporated during the rapid prototyping. Furthermore, there were some suggestions for the improvement of qCraft, which entailed that Automatic Observers had to work correctly, the inclusion of fermion entanglement and that qCraft should be upgraded to be compatible with version 1.8 of Minecraft.

Based on the results of the pretests, observations and interviews, five typologies were constructed from three different dimensions. These dimensions entailed the amount of preknowledge, the student having a critical or enthusiastic attitude towards the instruction or content and the performance level during the learning step of the interviews. The typologies derived from these dimensions were No preknowledge - Critical - Low performance, No preknowledge - Enthusiastic - High Performance, No preknowledge - Enthusiastic - Low Performance, Preknowledge - Critical - High Performance, and Preknowledge - Enthusiastic - High Performance.

There are still some areas in which the instruction can be improved. Most of the design choices are based on literature available for instructional design, but further improvements might be made by incorporating literature available for game design. Furthermore, there are still some misconceptions resulting from this instruction, such as the confusion with observer dependency and the effect of the angle of observation of Observer Dependent Blocks. This instruction also provides an alternative method of teaching quantum mechanics compared to those described in the studied literature, and more research might be conducted using this instruction as an example of a purely conceptual approach. This instruction also still needs to be summatively evaluated using quantitative analysis with proper physics students enrolled in secondary education in order to validate the instruction and to remove the sample bias resulting from the choice of the method for gathering respondents. After this validation, further research has to be conducted about the implementation factors such as the actual preknowledge of Dutch physics secondary education students. Furthermore, the exact embedding within the curriculum and the topics of the instruction after this instruction has to be determined. Finally, other games could also be investigated for the use of teaching quantum mechanics, such as the game Portal 2.

# References

- Adegoke, B. A. (2012). Impact of interactive engagement on reducing the gender gap in quantum physics learning outcomes among senior secondary school students. *Physics Education*, 47(4), 462 - 470. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1001308&site=ehost-live>
- Asikainen, M. A., & Hirvonen, P. E. (2014). Probing pre-and in-service physics teachers' knowledge using the double-slit thought experiment. *Science & Education*, 23(9), 1811 - 1833. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1040923&site=ehost-live>
- Baarda, D. B., de Goede, M. P. M., & Teunissen, J. (2009). *Basisboek kwalitatief onderzoek, handleiding voor het opzetten en uitvoeren van kwalitatief onderzoek* (2nd ed.). Houten: Noordhoff Uitgevers.
- Barnes, M. B., Garner, J., & Reid, D. (2004). The pendulum as a vehicle for transitioning from classical to quantum physics: History, quantum concepts, and educational challenges. *Science & Education*, 13(4-5), 417 - 436. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ925107&site=ehost-live>
- Bloom, B. S., Englehart, M. D., Furst, E. J., Hill, W. H., & Hrathwohl, D. R. (1956). *Taxonomy of educational objectives: Handbook i, cognitive domain*. New York: McKay.
- Cursussen leraar natuurkunde (professional master) tilburg — fontys.* (2015). Retrieved from \allowbreak<http://fontys.nl/Werk-en-studie/Opleidingen-en-cursussen/Leraar-Natuurkunde-Master/Studiekosten-59/Inhoud-opleiding/Cursussen.htm>
- Dori, Y. J., Dangur, V., Avargil, S., & Peskin, U. (2014). Assessing advanced high school and undergraduate students' thinking skills: The chemistry—from the nanoscale to microelectronics module. *Journal of Chemical Education*, 91(9), 1306 - 1317. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1040100&site=ehost-live>
- Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47(10), 777-780. doi: 10.1103/PhysRev.47.777
- Erduran, S. (2005). Applying the philosophical concept of reduction to the chemistry of water: Implications for chemical education. *Science & Education*, 14(2), 161 - 171. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ925087&site=ehost-live>
- Gianino, C. (2008). Energy levels and the de broglie relationship for high school students. *Physics Education*, 43(4), 429 - 432. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ802501&site=ehost-live>
- Griffiths, D. J. (2005). *Introduction to quantum mechanics* (2nd ed.). Delhi: Pearson education, inc.
- Groenen, E., Michels, B., Smeets, P., de Leeuw, A., van de Poppe, D., Bouwens, R., ... Meek, H. (2014, April). *Syllabus natuurkunde vwo centraal examen 2016, nader vastgesteld*. Utrecht.

- Henriksen, E. K., Bungum, B., Angell, C., Tellefsen, C. W., Frågåt, T., & Bøe, M. V. (2014). Relativity, quantum physics and philosophy in the upper secondary curriculum: Challenges, opportunities and proposed approaches. *Physics Education*, 49(6), 678 - 684. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1044233&site=ehost-live>
- Hobson, A. (2012). Teaching quantum nonlocality. *Physics Teacher*, 50(5), 270 - 273. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ984073&site=ehost-live>
- Hubber, P. (2006). Year 12 students' mental models of the nature of light. *Research in Science Education*, 36(4), 419 - 439. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ748089&site=ehost-live>
- Kirkpatrick, D. L. (1983, November). Four steps of measuring training effectiveness. *Personnel Administrator*, 28, 19-25.
- Kuttner, F., & Rosenblum, B. (2010). Bell's theorem and einstein's "spooky actions" from a simple thought experiment. *Physics Teacher*, 48(2), 124 - 130. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ876109&site=ehost-live>
- Laan, H. W. (2013, April). *Syllabus natuurkunde vwo centraal examen 2015*. Utrecht.
- Levrini, O., & Fantini, P. (2013). Encountering productive forms of complexity in learning modern physics. *Science & Education*, 22(8), 1895 - 1910. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1039645&site=ehost-live>
- Livio, M. (2008). *The golden ratio: The story of phi, the world's most astonishing number*. Paw Prints. Retrieved from <https://books.google.nl/books?id=w9dmPwAACAAJ>
- McKagan, S. B., Perkins, K. K., Dubson, M., Malley, C., Reid, S., LeMaster, R., & Wieman, C. E. (2008). Developing and researching phet simulations for teaching quantum mechanics. *American Journal of Physics*, 76(4), 406-417. Retrieved from <http://scitation.aip.org/content/aapt/journal/ajp/76/4/10.1119/1.2885199> doi: <http://dx.doi.org/10.1119/1.2885199>
- Müller, R., & Wiesner, H. (2002). Teaching quantum mechanics on an introductory level. *American Journal of physics*, 70(3), 200-209. doi: 10.1119/1.1435346
- Nieven, N., Folmer, E., & Vielgen, S. (2012). *Evaluation matchboard*. Enschede: SLO.
- Papaphotis, G., & Tsaparlis, G. (2008a). Conceptual versus algorithmic learning in high school chemistry: The case of basic quantum chemical concepts—part 1. statistical analysis of a quantitative study. *Chemistry Education Research and Practice*, 9(4), 323 - 331. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ888350&site=ehost-live>
- Papaphotis, G., & Tsaparlis, G. (2008b). Conceptual versus algorithmic learning in high school chemistry: The case of basic quantum chemical concepts—part 2. students' common errors, misconceptions and difficulties in understanding. *Chemistry Education Research and Practice*, 9(4), 332 - 340. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ888351&site=ehost-live>
- Plomp, T., Feteris, A., & Pieters, J. (1992). *Ontwerpen van onderwijs en trainingen* (W. Toic, Ed.). Utrecht: LEMMA.
- Singh, C. (2006). Assessing and improving student understanding of quantum mechanics. *Physics Education Research Conference*, 818, 69-72.

Singh, C., Belloni, M., & Christian, W. (2006). Improving students' understanding of quantum mechanics. *Physics Today*, 59(8), 43-49. doi: 10.1063/1.2349732

Smith, P. L., & Ragan, T. J. (2005). *Instructional design*. Oklahoma: John Wiley & Sons, Inc.

Thacker, B. A. (2003). A study of the nature of students' models of microscopic processes in the context of modern physics experiments. *American Journal of Physics*, 71(6), 599 - 606. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ679754&site=ehost-live>

Velentzas, A., Halkia, K., & Skordoulis, C. (2007). Thought experiments in the theory of relativity and in quantum mechanics: Their presence in textbooks and in popular science books. *Science & Education*, 16(3-5), 353 - 370. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ924554&site=ehost-live>

Verloop, N., & Lowyck, J. (2009). *Onderwijskunde, een kennisbasis voor professionals*. Houten: Noordhoff Uitgevers.

Wouters, P., & van Oostendorp, H. (2012, January). A meta-analytic review of the role of instructional support in game-based learning. *Computers & Education*, 60(1), 412-425. doi: 10.1016/j.comedu.2012.07.018

Zeilinger, A. (2005). *Einstiens spuk. teleportation und weitere mysterien der quantenphysik*. München: C. Bertelsman Verlag.

# Appendices

# Topics Mentioned in Literature

First, a description of the available topics within the domain of introductory quantum mechanics will be provided, because only then we can delve into the question how these topics could or should be taught to novice learners. This exploration would have to start with a topic the students are already familiar with. Such a topic is the Rutherford-Bohr Model of the Atom, also known as the Bohr Model, which presents a description of a hydrogen atom (see figure 8). Students in upper secondary education should at least be familiar with this model, especially those with a technical profile. This gives way to introduce the students to the concept of elementary particles, which are the particles which exhibit quantum behaviour. The Bohr-model is also often referred to in the studied literature (Dori et al., 2014; McKagan et al., 2008; Müller & Wiesner, 2002; Papaphotis & Tsaparlis, 2008a, 2008b).

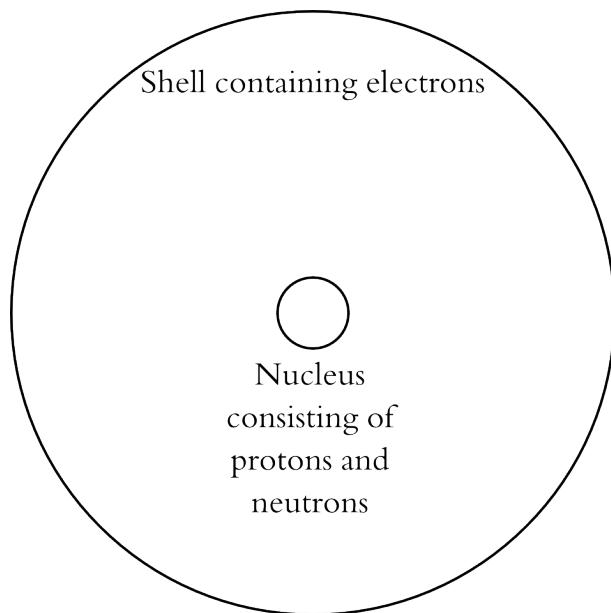


Figure 8: The Rutherford-Borh Model of the Atom

Some of the studies (Erduran, 2005; Hubber, 2006; Müller & Wiesner, 2002; Thacker, 2003) then describe properties of specific elementary particles, mostly of electrons or photons. Often used properties are the photoelectric effect or the polarisation of light (Henriksen et al., 2014; McKagan et al., 2008; Müller & Wiesner, 2002). These properties could give more meaning to what the elementary particles are and do. Another benefit would be that these properties are used in the various experiments conducted within the field of quantum mechanics.

The double-slit experiment is the most famous of these experiments, and also the most studied tool for educational purposes (Asikainen & Hirvonen, 2014; Henriksen et al., 2014; Hobson, 2012; Levrini & Fantini, 2013; McKagan et al., 2008; Müller & Wiesner, 2002; Papaphotis & Tsaparlis, 2008a; Singh et al., 2006; Thacker, 2003). A reason why this experiment is famous is because it was the first experiment in history to demonstrate phenomena of quantum mechanics. The experiment entails shooting elementary particles through two narrow slits in a wall, projecting them on a large wall behind these two slits. When the two slits are separated just a small amount, an interference pattern emerges. This is a

result expected when the elementary particles would not be particles but waves. However, if the particles are observed and information is available through which slit each particle traversed, a diffraction pattern emerges, which would be the behaviour of particles. The most apparent phenomena demonstrated by this experiment is the wave-particle duality of elementary particles, which then could give way to mathematical descriptions of quantum mechanics like the Schrödinger equation. The Centraal Eindexamen of 2015 also already contained this experiment (Laan, 2013), so educational resources for teaching this experiment already exist.

For understanding the double-slit experiment, the concept of superposition is vital. Superposition means that when a particle is not observed, it is in all possible states at the same time. In the case of the double-slit experiment, superposition means that the particle goes through both slits at the same time. It then interferes with itself because of the probability function of where the particle ends up. However, when the particle is observed through which slit it travels, the information through which slit the particle travels is known and forces the probability function of the particle to collapse to either the left or the right slit. Because of this, it behaves like a particle and a diffraction pattern emerges. A video which demonstrates the double-slit experiment can be seen on [https://upload.wikimedia.org/wikipedia/commons/transcoded/e/e4/Wave-particle\\_duality.ogv/Wave-particle\\_duality.ogv.480p.webm](https://upload.wikimedia.org/wikipedia/commons/transcoded/e/e4/Wave-particle_duality.ogv/Wave-particle_duality.ogv.480p.webm). The double-slit experiment can provide the learner with an explanation of the observer dependency of the elementary particles. However, only Müller and Wiesner (2002) mentions this concept in his study, and it also does not appear in the Centraal Eindexamen of 2016 (Groenen et al., 2014).

The concept of superposition also has different cases. There are other properties of elementary particles which can be in superposition, for example the polarity of photons. Upon measurement, the polarisation value of a photon particle collapses to a certain value, but before this collapse it has all the different polarities at the same time. This gives way to the concept of entanglement, mentioned in some studies (Henriksen et al., 2014; Hobson, 2012; Kuttner & Rosenblum, 2010). Entanglement is a phenomenon which occurs between elementary particles, and it has as effect that the collapse of the different particles are interdependent of each other. This entanglement has two forms: boson entanglement and fermion entanglement. When the two particles are bosons, they always collapse to the same state on observation, and when the two particles are fermions, they always collapse to each others opposite state.

Since the discovery of the phenomena occurring within quantum mechanics, scientists have debated fiercely about how to interpret these phenomena (Barnes et al., 2004). Roughly speaking, the scientists could be divided into two interpretations: the interpretation of the realists and the interpretation of the ontologists. The realists thought that there has to be something underneath quantum mechanics which could explain the strange phenomena of superposition and entanglement, whereas the ontologists thought that the phenomena of quantum mechanics stand on its own. The phenomena of entanglement played a huge role in this debate. The realists first thought that they could use entanglement to prove that there is a reality underneath quantum mechanics, but it eventually led mostly to evidence towards the camp of ontologists. One example of this is Bell's inequalities (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002), which is beyond the scope of this literature study to explain.

Henriksen et al. (2014) writes that there are three main differences between classical mechanics and quantum mechanics. The first difference is the fact that classical mechanics are deterministic and that quantum mechanics are probabilistic, also brought up by Levrini and Fantini (2013) and by Papaphotis and Tsaparlis (2008a). Classical mechanics rely heavily on deterministic causal effects, which can ultimately be explained. This is very apparent in systems of force, where everything moves according to certain laws, take for example the three Newtonian laws. Quantum mechanics however relies heavily on probabilistic models, where certain properties of certain elementary particles collapse to certain values according to probability functions.

A second difference between classical mechanics and quantum mechanics mentioned by Henriksen et al. (2014) is the locality of classical mechanics and the non-locality of quantum mechanics, also mentioned by Hobson (2012). On the scale of classical mechanics, it is possible to determine the exact position of an object, at least it is possible to do this on a significant scale. On a very small scale however, on the scale of quantum mechanics, the exact position of an object cannot be determined. There is an

inherent uncertainty about the position of an object, which is very small and insignificant on the scale of classical mechanics, but quite significant on the scale of elementary particles. This is also true for the momentum of an elementary particle, which can be translated to the speed of an elementary particle. This uncertainty can be demonstrated by the uncertainty principle of Heisenberg (Henriksen et al., 2014; Müller & Wiesner, 2002; Velentzas et al., 2007), which has as implications that neither the location nor the momentum of an elementary particle can be exactly known and that the more certain the location of an elementary particle is known, the less certain the momentum of an elementary particle can be known and vice versa.

Finally, Henriksen et al. (2014) mentions that classical mechanics are continuous and that quantum mechanics are discrete. This is because of the Planck length, which is the shortest measurable length. In classical mechanics, this length is very insignificant, and because of that the world looks continuous. A fully continuous world would mean that there is no tiniest unit, but that it is always possible to “go smaller”. For example, if one had a plank of wood, it could be divided in half infinitesimally. However, on a quantum scale, this is not possible, because it is not possible to have something smaller than the Planck length.

Because of the inherent difficulty with quantum mechanics, some scientists have posited thought experiments, which allows the learner to make a mental model about the different concepts of quantum mechanics. The most famous thought experiment is that of Schrödinger’s cat (Müller & Wiesner, 2002; Velentzas et al., 2007), where the life of a cat depends on the collapse of an elementary particle. When the cat is then observed, the state of the elementary is observed indirectly, which causes it to collapse and either kill the cat or let the cat live. This teaches the student about observer dependency, the way observations are linked to the random collapse of an elementary particle. Another thought experiment mentioned in the studied literature is the EPR paradox (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002; Velentzas et al., 2007), which can be used to teach the student about how entanglement is related to deep questions about the nature of quantum mechanics. This thought experiment however is related to the EPR experiment, which lies beyond the scope of this study to explain.

Finally, there are some studies which recommend certain mathematical approaches to quantum mechanics, namely the Schrödinger’s equation (Müller & Wiesner, 2002; Singh et al., 2006), the Hermitian operator (Singh et al., 2006), the aforementioned Bell’s inequalities (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002), the eigenvalue equation (Müller & Wiesner, 2002) and the DeBroglie energy levels (Dori et al., 2014; Gianino, 2008; McKagan et al., 2008). However, these mathematical approaches rely on a thorough conceptual understanding of quantum mechanics and are therefore not relevant to this study.

The topics relevant to teaching quantum mechanics can be summed up as the Rutherford-Bohr model of the Atom and elementary particles, the double-slit experiment, superposition, entanglement, the debate between realists and ontologists, the differences with classical mechanics, thought experiment and the mathematical side of quantum mechanics.

# Topical Domains

Each instruction should start with a reason why the student might be interested in learning the subject. This is established by stating the relevance of quantum mechanics by enlisting the different applications of quantum mechanics.

When the student knows why he should learn about quantum mechanics, the instruction continues with what the student already might know, because this activates the brain regions containing this information, making it possible for the student to connect the new knowledge with what he already knows. As already stated in the *Learner Analysis* on page 17, the student should already be familiar with the Rutherford-Bohr model of the Atom. This thereupon leads easily into the next domain, namely that of the *Elementary Particles*. Here, the student learns about the particles which demonstrate quantum behaviour.

When learned about the existence of elementary particles, the student can also learn about *Classical Communication*. This needs understanding about elementary particles, for these are the particles which are used to conduct classical communication. Classical communication is relevant to quantum mechanics for two reasons. The first reason is that it connects the mysterious elementary particles to the daily experience. Everyone uses the internet everyday, which uses classical communication. Therefore, the student should already be familiar with the concept. The second reason is that it is a prerequisite for learning about quantum teleportation, which will be explained later on in this section.

It might strike the reader that the famous double-slit experiment is not entailed within the learning objectives. There are two reasons for not including this experiment in the instruction. First of all, the double-slit is already part of the standard curriculum (Laan, 2013), so there is no need to develop educational material for it. The second and more important reason is that the double-slit experiment can be used to demonstrate the relations between the concepts within quantum mechanics, but to fully comprehend these relations the student should first learn the concepts themselves. The term "wave-particle duality" also does not hold any meaning if the student is still unaware of the probabilistic nature of quantum mechanics. However, this instruction could be followed up by instruction covering the double-slit experiment.

The first concept underlying the double-slit experiment is *Observer Dependency*. This is also the first time the student is confronted by one of the more counterintuitive concepts of quantum mechanics. It teaches the student that quantum mechanics cannot only be explained by pure determinism and causal relations, but that quantum mechanics has a probabilistic nature. The student learns this concept by examining what happens if a property of an elementary particle is observed.

The probabilistic nature of quantum mechanics is further explored with the debate between *Realism and Ontology*. This section starts with the realist interpretation of quantum mechanics, which entails that there must be an explanation for the seemingly random behaviour of elementary particles, it is only not possible to measure with the current level of technology. The ontologist explanation however is that there is no explanation of the random behaviour of elementary particles, and it is the inherent nature of quantum mechanics. With this debate, the student is challenged to evaluate his own beliefs about the nature of physics. Most likely, he will start at the realistic interpretation, and this is a natural way to teach the student to let him think about the other interpretation.

After this historical and philosophical intermezzo, the student is then introduced to the second concept underlying the double-slit experiment, which is *Superposition*. This concept can only be fully understood when the student is aware of the ontologist interpretation, for it involves comprehension of

the fact that quantum mechanics is truly probabilistic. This is because the student has to understand that before measurement, the elementary particle has no true defined state yet, and is in all different states at the same time.

The next concept the student is introduced to is the concept of *Entanglement*, which teaches the student that the behaviour of elementary particles is not entirely random. Although the collapse of two entangled particles is fundamentally random, the two particles are interdependent. This means that the particles can either collapse to the same state on observation in the case of bosons, or that the particles collapse to each others opposite state in the case of fermions. This concept could be used to develop further in the EPR experiment, which was an attempt of realist interpreters to prove that there is an underlying explanation of quantum mechanics, but ultimately led to more evidence for the ontologist interpretation. The EPR experiment makes way for topics like the hypothesis of locality, the hidden variable hypothesis and Bell's inequalities. However, this instruction will limit itself to only explaining the concept of entanglement itself, for the EPR experiment is quite sizeable and fits in an entire separate instruction.

The next topic is the *Uncertainty Principle of Heisenberg*, which stands a bit on its own. It can be used to teach the student about the non-locality of quantum mechanics, because it demonstrates that the specific location or the specific speed of an elementary particle cannot be known exactly, and there is an inherent uncertainty about these two variables. Furthermore, it also has a different realist and ontologist interpretation. To understand the ontologist interpretation, it is important that the student is already taught about superposition. The reason why this topic is included in the instruction is because it is another counterintuitive but central concept within quantum mechanics, and it is regarded as important for teaching by Henriksen et al. (2014). The principle is also one of the few topics directly included in the Centraal Eindexamen 2016 (Groenen et al., 2014) within this instruction. Finally, it also ties in with the next domain.

This last domain is *Teleportation*, which teaches the student about the inner workings of entanglement in the real world. This topic will first explain what it is not, but is easily confused with, namely the teleportation used in science-fiction. To argue that this is actually not possible, the student has to use the uncertainty principle of Heisenberg. This is also the main reason that it is included, all the topics taught before have to be used in the Teleportation experiment, it can therefore serve as a conclusion of the instruction by letting the student go through all the different domains one more time.

# Prerequisite Graph of the Topical Domains

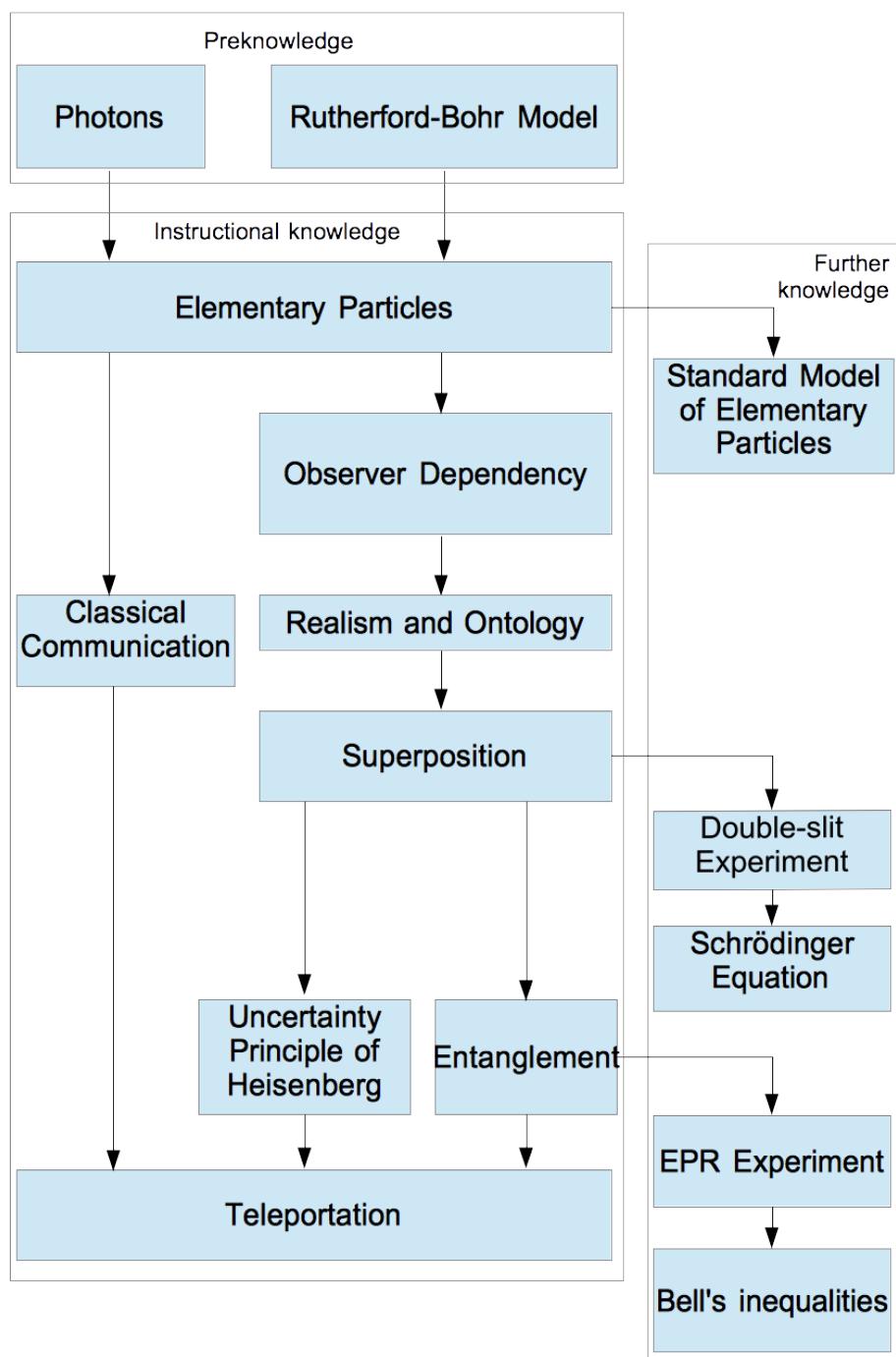


Figure 9: A display of the different topical domains and their prerequisite order

# Learning Objectives

#	Name	Prerequisite	Taxonomy of bloom	Domain
1	The student can list the different applications of quantum mechanics		Knowledge	Applications of Quantum Mechanics
2	The student can state that everything we observe exists out of molecules		Knowledge	Preknowledge
3	The student can state that molecules exist out of atoms	2	Knowledge	Preknowledge
4	The student can state that atoms exist out of protons, neutrons and electrons	3	Knowledge	Preknowledge
5	The student can state what a photon is		Knowledge	Preknowledge
6	The student can state the speed of light	5	Knowledge	Probably preknowledge
7	The student can state the value of the diameter of an atom	3	Knowledge	Might be preknowledge
8	The student can state the value of the Planck Constant		Knowledge	Might be preknowledge
9	The student can state that protons exist out of 2 up-quarks and 1 down-quark	4	Knowledge	Might be preknowledge
10	The student can state that neutrons exist out of 1 up-quark and 2 down-quarks	4	Knowledge	Might be preknowledge
11	The student can state that protons and neutrons are about as heavy, and that electrons have an insignificant weight compared to the other two	4	Knowledge	Preknowledge
12	The student can state that opposite charged particles attract each other	4	Knowledge	Preknowledge
13	The student can state that protons are positively charged	4	Knowledge	Preknowledge
14	The student can state that electrons are negatively charged	4	Knowledge	Preknowledge

15	The student can state that neutrons do not have any charge	4	Knowledge	Preknowledge
16	The student can state that photons, electrons and quarks are elementary particles	9, 10	Knowledge	Elementary Particles
17	The student can state the definition of an elementary particle	16	Knowledge	Elementary Particles
18	The student can explain what an elementary particle is	17	Comprehension	Elementary Particles
19	The student can state that classical Communication happens by sending particles through a channel	18	Knowledge	Classical Communication
20	The student can state that no particle can travel faster than light	6	Knowledge	Classical Communication
21	The student can explain why messages through a classical communication channel cannot travel faster than the speed of light	19, 20	Comprehension	Classical Communication
22	The student can calculate the time needed to send a message from location A to location B using classical communication given the distance between A and B	21	Application	Classical Communication
23	The student can state certain properties of elementary particles	11, 12, 13, 14, 15	Knowledge	Observation Dependency
24	The student can state that a property of an elementary particle collapses to a certain value on observation	23	Knowledge	Observation Dependency
25	The student can state that the collapse of a property of an elementary particle to a certain value is random	24	Knowledge	Observation Dependency
26	The student can explain what happens to the property of an individual elementary particle if it is observed	25	Comprehension	Observation Dependency
27	The student can list the two different interpretations of quantum mechanics		Knowledge	Realism and Ontology
28	The student can state the realist interpretation of the collapse of a property	26, 27	Knowledge	Realism and Ontology
29	The student can state the ontologist interpretation of the collapse of a property	26, 27	Knowledge	Realism and Ontology
30	The student can explain the realist interpretation of quantum mechanics	28	Comprehension	Realism and Ontology
31	The student can explain the ontologist interpretation of quantum mechanics	29	Comprehension	Realism and Ontology

32	The student can differentiate between a realist interpretation and an ontological interpretation of quantum mechanics, given a statement of either a realist interpretation or an ontologist interpretation	30, 31	Comprehension	Realism and Ontology
33	The student can state that before observing a property of an elementary particle, it is in a state of superposition	31	Knowledge	Superposition
34	The student can state the definition of superposition	33	Knowledge	Superposition
35	The student can explain in what state the property of an elementary particle is before observing this property	34	Comprehension	Superposition
36	The student can state the definition of entanglement	26	Knowledge	Entanglement
37	The student can state that entanglement occurs between two elementary particles	27	Knowledge	Entanglement
38	The student can state that entanglement can take place no matter the distance between the two particles	37	Knowledge	Entanglement
39	The student can state that entanglement can take place no matter when each particle is observed	37	Knowledge	Entanglement
40	The student can list the two different types of entanglement	28	Knowledge	Entanglement
41	The student can state that the properties of two boson entangled particles always collapse to the same state	29	Knowledge	Entanglement
42	The student can state that the properties of two fermion entangled particles always collapse to each others opposite state	29	Knowledge	Entanglement
43	The student can explain what happens to the properties of two entangled particles on observation	41, 42	Comprehension	Entanglement
44	The student can use entanglement to predict which state the property of a particle will collapse to, given the state of the property of an entanglement particle and the type of entanglement between the two particles	43	Application	Entanglement
45	The student can deduce the type of entanglement given the states of a common property between two entanglement particles	43	Analysis	Entanglement
46	The student can state the uncertainty principle of Heisenberg	8, 17	Knowledge	Uncertainty Principle of Heisenberg

47	The student can explain the meaning of each variable in the uncertainty principle of Heisenberg	46	Comprehension	Uncertainty Principle of Heisenberg
48	The student can explain why the exact location or momentum cannot be known according to the uncertainty principle of Heisenberg	47	Comprehension	Uncertainty Principle of Heisenberg
49	The student can explain why the position has to be lesser known if the momentum is better known and vice versa according to the uncertainty principle of Heisenberg	47	Comprehension	Uncertainty Principle of Heisenberg
50	The student can explain why the uncertainty principle of Heisenberg is only significant when dealing with very small objects	7, 47	Comprehension	Uncertainty Principle of Heisenberg
51	The student can differentiate between the measurement of the location of a planet and the measurement of the location of an electron	50	Comprehension	Uncertainty Principle of Heisenberg
52	The student can list the steps of teleportation in science-fiction movies		Knowledge	Teleportation
53	The student can explain why science-fiction teleportation is not possible	48	Comprehension	Teleportation
54	The student can list the steps of quantum teleportation	43	Knowledge	Teleportation
55	The student can explain what happens when conducting quantum teleportation	54	Comprehension	Teleportation
56	The student can apply the correct step from the quantum teleportation experiment, given a certain situation	55, 44, 45	Application	Teleportation
57	The student can deduce why quantum teleportation cannot be used to communicate instantly with someone on a different location	55	Analysis	Teleportation

Table 6: A complete outline of the learning objectives used for the instruction. With each learning objective, the name, the direct prerequisites, the category within the taxonomy of Bloom and the domain is provided.

# Learning Objectives and Standards

1. The student can list the different applications of quantum mechanics
  - (a) The student enlists the transistor as an application of quantum mechanics
  - (b) The student enlists the laser as an application of quantum mechanics
  - (c) The student enlists quantum computing as a possible future application of quantum mechanics
2. The student can state that everything we observe exists out of molecules
3. The student can state that molecules exist out of atoms
4. The student can state that atoms exist out of protons, neutrons and electrons
5. The student can state what a photon is
  - (a) The student states that a photon is a light particle
6. The student can state the speed of light
  - (a) The student states that the speed of light is about  $3.0 \cdot 10^8$  m/s
7. The student can state the value of the diameter of an atom
  - (a) The student states that the value of the diameter of an atom is 0.1 to 0.5 nm
8. The student can state the value of the reduced Planck Constant
  - (a) The student states that the Planck Constant is  $1.0 \cdot 10^{-34}$  Js
9. The student can state that protons exist out of 2 up-quarks and 1 down-quark
10. The student can state that neutrons exist out of 1 up-quark and 2 down-quarks
11. The student can state that protons and neutrons are about as heavy, and that electrons have an insignificant weight compared to the other two
12. The student can state that opposite charged particles attract each other
13. The student can state that protons are positively charged
14. The student can state that electrons are negatively charged
15. The student can state that neutrons do not have any charge
16. The student can state that photons, electrons and quarks are elementary particles
17. The student can state the definition of an elementary particle
  - (a) The student states that it is a particle of which its substructure is not known

18. The student can explain what an elementary particle is
  - (a) The student uses the definition of an elementary particle to explain what it is
  - (b) The student states that some scientists believe they have no substructure
19. The student can state that classical communication happens by sending particles through a channel
20. The student can state that no particle can travel faster than light
21. The student can explain why messages through a classical communication channel cannot travel faster than the speed of light
  - (a) The student states that particles are used in certain pattern for classical communication
  - (b) The student states that in order to communicate from one location to another, the particles have to travel between the locations through a communication channel
  - (c) The student states that no particles can travel faster than light
22. The student can calculate the time needed to send a message from location A to location B using classical communication given the distance between A and B
  - (a) The student divides the distance by the speed of light to derive the time needed
23. The student can state certain properties of elementary particles
  - (a) The student states charge as a property of an elementary particle
  - (b) The student states polarisation as a property of photons
24. The student can state that a property of an elementary particle collapses to a certain value on observation
25. The student can state that the collapse of a property of an elementary particle to a certain value is random
26. The student can explain what happens to the property of an individual elementary particle if it is observed
  - (a) The student states that a property of an individual elementary particle will collapse to a random state upon observation
27. The student can list the two different interpretations of quantum mechanics
  - (a) The student enlists realism as an interpretation of quantum mechanics
  - (b) The student enlists ontology as an interpretation of quantum mechanics
28. The student can state the realist interpretation of the collapse of a property
  - (a) The student states that the realist interpretation of the collapse of a property has an underlying explanation or mechanic which we do not have the technology available for to measure
29. The student can state the ontologist interpretation of the collapse of a property
  - (a) The student states that the ontologist interpretation of the collapse of a property has no underlying explanation or mechanic but is inherently random
30. The student can explain the realist interpretation of quantum mechanics
  - (a) The student states that the realist interpretation of quantum mechanics is that every physical theory is grounded in reality

- (b) The student states that realists believe that every theory can be explained by classical mechanics
  - (c) The student states that realists believe that even the seemingly random phenomena occurring within quantum mechanics can eventually be explained by the rules of classical mechanics
31. The student can explain the ontologist interpretation of quantum mechanics
- (a) The student states that the ontologist interpretation of quantum mechanics is that there is no underlying explanation of quantum mechanics
  - (b) The student states that the ontologist interpretation of quantum mechanics is that quantum mechanics is real and happens on its own
32. The student can differentiate between a realist interpretation and an ontological interpretation of quantum mechanics, given a statement of either a realist interpretation or an ontologist interpretation
33. The student can state that before observing a property of an elementary particle, it is in a state of superposition
34. The student can state the definition of superposition
- (a) The student states that if a property is in superposition, its state is in all states at the same time
35. The student can explain in what state the property of an elementary particle is before observing this property
- (a) The student states that the property is in all states at the same time and collapses to a specific state upon observation
36. The student can state the definition of entanglement
- (a) The student states that entanglement entails an interdependence within the collapse of two elementary particles
37. The student can state that entanglement occurs between two elementary particles
38. The student can state that entanglement can take place no matter the distance between the two particles
39. The student can state that entanglement can take place no matter when each particle is observed
40. The student can list the two different types of entanglement
- (a) The student enlists boson type entanglement
  - (b) The student enlists fermion type entanglement
41. The student can state that the properties of two boson entangled particles always collapse to the same state
42. The student can state that the properties of two fermion entangled particles always collapse to each others opposite state
43. The student can explain what happens to the properties of two entangled particles on observation
- (a) The student state that dependent on the type of entanglement, the property of the particles either collapse to the same state or each others opposite state

- (b) The student states that if the particles are boson type entangled, the properties will always collapse to the same state upon observation
  - (c) The student states that if the particles are fermion type entangled, the properties will always collapse to each others opposite state upon observation
44. The student can use entanglement to predict which state the property of a particle will collapse to, given the state of the property of an entanglement particle and the type of entanglement between the two particles
- (a) If the particles are bosons, the student argues that the state to which the property will collapse will be the same as the state of the property of the entangled particle
  - (b) If the particles are fermions, the student argues that the state to which the property will collapse will be the opposite of the state of the property of the entangled particle
45. The student can deduce the type of entanglement given the states of a common property between two entanglement particles
- (a) The student argues that if the states of the common property are the same, the two particles must be bosons
  - (b) The student argues that if the states of the common property are the opposite, the two particles must be fermions
46. The student can state the uncertainty principle of Heisenberg
- (a) The student states that the uncertainty principle of Heisenberg can be expressed as  $\sigma x \cdot \sigma p \geq \frac{\hbar}{2}$
47. The student can explain the meaning of each variable in the uncertainty principle of Heisenberg
- (a) The student states that the  $\sigma$  symbol is an expression of uncertainty
  - (b) The student states that the  $x$  refers to the location of the particle
  - (c) The student states that the  $p$  refers to the momentum of the particle
  - (d) The student states that the momentum is an expression of the speed of a particle
  - (e) The student states that the  $\geq$  symbol expresses "greater or equal than"
  - (f) The student states that the  $\hbar$  symbol refers to the reduced Planck constant
  - (g) The student summarises this as that the product of uncertainty in location and uncertainty in momentum has to be greater or equal than the reduced Planck constant divided by 2
48. The student can explain why the exact location or momentum cannot be known according to the uncertainty principle of Heisenberg
- (a) The student argues that if either  $\sigma x$  or  $\sigma p$  is 0,  $\sigma x \cdot \sigma p$  is also 0, and that violates the principle
  - (b) The student states that this means that neither the uncertainty in location nor the uncertainty in momentum can be 0
49. The student can explain why the position has to be lesser known if the momentum is better known and vice versa according to the uncertainty principle of Heisenberg
- (a) The student argues that if  $\sigma x$  becomes smaller,  $\sigma p$  has to become bigger, for else  $\sigma x \cdot \sigma p > \frac{\hbar}{2}$
  - (b) The student states that this means that if the uncertainty in location decreases, the uncertainty in momentum increases
50. The student can explain why the uncertainty principle of Heisenberg is only significant when dealing with very small objects

- (a) The student argues that  $\hbar$  is an insignificantly tiny number when referring to the scale of daily experiences
  - (b) The student argues that only when the scale decreases to that of the width of an atom,  $\hbar$  becomes significant
51. The student can differentiate between the measurement of the location of a planet and the measurement of the location of an electron
- (a) The student argues that because  $\hbar$  is insignificant on the scale of a planet, the location of a planet is relatively certain
  - (b) The student argues that  $\hbar$  is significant on the scale of an electron, and because of this the location of an electron is relatively uncertain
52. The student can list the steps of teleportation in science-fiction movies
- (a) The student states that first the object at the first station is scanned
  - (b) The student states that by scanning the object, all the information about all of the particles within the object are measured
  - (c) The student states that then this information is used at the second station to build an exact copy of the object at the first station
  - (d) The student states that the object at the first station is now completely destroyed
53. The student can explain why science-fiction teleportation is not possible
- (a) The student argues that because of the uncertainty principle of Heisenberg, all information about the object at the first station cannot be exactly determined
  - (b) The student argues that because the objects at the first station cannot be exactly determined, it is not possible to build an exact copy at the second station
54. The student can list the steps of quantum teleportation
- (a) The student states that Alice has a particle X
  - (b) The student states that Alice gets particle A and Bob gets particle B, which are entangled from a quantum channel
  - (c) The student states that Alice executes a Bell Measurement with a combination of A and X, this way X loses its individual properties, these properties are given to B
  - (d) The student states that Alice now knows the type of entanglement between particle A and particle B
  - (e) The student states that particle B can arrive in two different states, because there are two different forms of entanglement possible
  - (f) The student states that Alice transmits the type of entanglement to Bob via a classical channel
  - (g) The student states that with this information, Bob can determine the state of particle X
  - (h) The student states that Bob now transmits the state of particle B and his prediction for the state of particle X to Alice, so she can confirm whether the teleportation was successful
55. The student can explain what happens when conducting quantum teleportation
- (a) The student states that because particle A and B are entangled and particle X loses its individual properties to particle B, particle X and B are entangled
  - (b) The student states that because Bob learns the type of entanglement from Alice, he now can derive the state of particle X

- (c) The student states that quantum teleportation means that information about the state of particle X is transmitted to particle B via entanglement
56. The student can apply the correct step from the quantum teleportation experiment, given a certain situation
57. The student can deduce why quantum teleportation cannot be used to communicate instantly with someone on a different location
- (a) The student argues that an elementary particle cannot be influenced to collapse to a certain value on observation, but that it collapses to a random state.
  - (b) The student argues that this would be necessary to send a message from Alice to Bob
  - (c) Furthermore, the student argues that Bob still needs information from Alice via a classical communication channel about the type of entanglement, for else he cannot determine the state of particle X

# Initial Framework for the Instruction

## Minecraft Tutorial

- Moving
  - A sign telling the student to look around by using the mouse
  - A sign on the other side telling the student to move around by using the WASD keys
- Jumping
  - A sign telling the student to use the spacebar to jump
  - One horizontal bar of one block high forcing the student to jump over it in order to progress
  - One vertical gap of one block high forcing the student to jump over it in order to progress
- Redstone
  - Signals
    - \* One redstone torch connected to a redstone lamp, showing the active signal emitted by a redstone torch
    - \* One normal torch connected to a redstone lamp, showing no signal emitted by a normal torch and providing a point of reference
    - \* One redstone block connected to a redstone lamp, showing the active signal emitted by a redstone torch
    - \* One normal block connected to a redstone lamp, showing no signal emitted by a normal torch and providing a point of reference
    - \* The gestalt principle of separation is used to cluster the torches and the blocks
  - Interaction
    - \* A sign telling the student to use the right mouse button in order to interact with objects
    - \* A lever connected to a redstone lamp
    - \* A button connected to a redstone lamp
    - \* A wooden pressure plate connected to a redstone lamp
    - \* A tripwire hook system connected to a redstone lamp
    - \* An iron door at the end, preventing the student from continuing until he has activated every redstone lamp at least once
  - Input blocks
    - \* A lever connected to an iron door
    - \* A lever connected to a sticky piston with an iron block
    - \* A lever connected to a dropper with netherstars
    - \* An iron door at the end, preventing the student from continuing until he has activated every lever at least once

- Messaging system
  - A pillar with a button connected to a command block which generates a message through the message system
  - An iron door preventing the student from continuing until he has pressed the button
- Inventory
  - A sign telling the student to use the E key in order his inventory
  - A chest containing a paper named "ticket"
  - An iron door at the end preventing the student from continuing
  - A dropper in which the ticket can be inserted, upon which the iron door opens
- Use items and read books
  - A sign telling the student to use the right mouse button in order to activate items in his inventory
  - A book in a chest
  - A button at the end of the room, teleporting the student to the qCraft museum

## Introduction

- Attention
  - (Beginning of book)
  - It welcomes the student to Minecraft
  - The writer introduces himself as Professor qCraft
- Purpose
  - The professor wants to show the student his work on Quantum Blocks
  - The professor mentions different concepts of quantum mechanics:
    - \* Superposition
    - \* Entanglement
    - \* Quantum Teleportation
- Interest or Motivation
  - The professor is trapped within his office, and the student has to rescue him
  - The professor has a communication system available, so he can guide the student
  - (End of book)
- Preview
  - The student teleports to the qCraft museum
  - This is a big hallway with closed iron doors at both sides and a dropper with a sign saying "Tickets" at the other side
  - The doors have signs above them which indicate the topic beyond that door:
    - \* The Microscopic World
    - \* Theory of Relativity
    - \* Observer Dependency

- \* Quantum Blocks
- \* Entanglement
- \* Tutorial II
- \* Realism and Ontology
- \* The Uncertainty Principle of Heisenberg
- \* Teleportation
- \* Office of Professor qCraft
- When teleporting to the museum, the student received a paper with the name "The Microscopic World"
- Upon putting this paper into the dropper, the corresponding iron door opens up
- Behind the iron door is a button which teleports the student to the next branch

## Body

### The Rutherford-Bohr Model of the Atom (Declarative Knowledge)

- A chest with a book
- Two pictures on the wall:
  - A picture of Niels Bohr
  - A picture of the Rutherford-Bohr Model of the Atom similar to figure 8 on page 79
- Prior Knowledge
  - (Beginning of book)
  - Everything around us exists out of molecules
  - Molecules exist out of atoms
  - Atoms are made out of a core, the nucleus, and a shell, the electrons
  - The nucleus of an atom exists out of protons and neutrons
  - The electrons stay in the shell of an atom, because electrons and protons are attracted to each other
  - At this point the book refers to a picture shown on a wall, which depicts the Rutherford-Bohr Atom Model
  - This attraction is caused by electrons having a negative charge and protons having a positive charge
  - Neutrons do not have any charge
  - There are other nanoscopic particles, a very famous one is the photon
  - The photon is known as the light particle

### Elementary Particles (Concept)

- Information and examples
  - A proton or a neutron consists out of three quarks
  - Quarks, electrons and photons are considered to be elementary particles
  - An elementary particle is a particle of which we don't know its substructure
  - This means that we don't know what the elementary particles are composed of

- Focus attention
  - The book emphasises that it is sufficient to know that elementary particles exist, and that these are the particles which demonstrate quantum behaviour
  - End of book
- Learning strategies
  - To enhance learning, the concepts are combined in the picture on the wall depicting the Rutherford-Bohr Model of the Atom
- Practice and Feedback
  - After reading the book, the student has to go through a multiple choice test
    - \* An atom consists out of:
      - A nucleus and shell (correct)
      - Photons
    - \* The shell of an atom consists out of:
      - Photons
      - Neutrons
      - Electrons (correct)
      - Quarks
    - \* The nucleus of an atom consists out of:
      - Molecules
      - Protons ad Neutrons (correct)
      - Electrons
      - It is an elementary particle
    - \* Select all the particles that we consider to be elementary particles:
      - Photons (correct)
      - Atoms
      - Electrons (correct)
      - Protons
      - Neutrons
      - Quarks (correct)
    - \* The test is represented by a long hallway with closed iron doors
    - \* Between the iron doors are buttons or levers with signs depicting the multiple choice answers, of which the correct ones open the next door
    - \* Every time the student goes through the next door, the next question pops up in the message system
  - At the end of each branch is a chest with the ticket to the next branch. When the student has taken the ticket, he is teleported back into the museum

### Theory of Relativity and Classical Communication (Declarative Knowledge)

- A chest with a book
- A contraption on the side
  - Two lamps
  - Connected with redstone repeaters

- Which is connected to a redstone clock
- Every second the first lamp turns on and off, then a signal travels through the repeaters and finally the second lamp turns on and off
- Prior Knowledge
  - (Beginning of book)
  - Protons, neutrons and electrons have mass
  - Protons and neutrons have an almost equal mass
  - Electrons have a very small mass in comparison to protons and neutrons
  - Photons do not have any mass
- Information and examples
  - According to the relativity theory of Einstein, the more mass an object or a particle has, the slower its maximum speed is
  - Because photons do not have any mass, they travel with the fastest speed possible
  - The speed of photons, also known as light speed, is about 300 000 000 m/s
  - The speed with which photons travel is constant
  - All other elementary particles travel slower than photons, but can still travel with 99% of the light speed
  - When communicating from one place to another, particles are sent between the two locations through a channel or cable
  - This is called classical communication
  - For example, if the channel is a glass fibre cable, photons are used
- Focus attention
  - The important aspect is that there is a limit with which elementary particles travel
  - Therefore, classical communication is not instant
- Practice
  - The student has to calculate the time needed to communicate given the distance between the two locations
  - The distance is 1 000 000 m
- Feedback
  - When the student grabs the ticket at the end of the room to teleport back to the main hallway, the correct answer is displayed in the message system (0.003 s)

## Observer Dependency (Concept)

- Information and examples
  - A message appears in the message system, telling the student to find the difference between the two blocks in front of him
  - The left block is a static block with the diamond block type
  - The right block is an Observer Dependent Block
    - \* If the block is observed from the back-to-front axis, the block has a diamond block type

- \* If the block is observed from the perpendicular axis, the block has a redstone block type
- At the end of the room is a iron door, which opens up if the Observer Dependent Block resolves to a redstone block type
- Focus attention
  - By comparing the two blocks, the student finds the difference in behaviour between the two blocks
  - This leads to an understanding of the behaviour of Observer Dependent Blocks
  - This gives way to teach the student about Observer Dependency
- Learning strategies
  - The Observer Dependent Block visualises the effect of observation without oversimplifying it
  - The behaviour still has to be linked to the term Observer Dependency, which will happen in the next book
  - The behaviour still has to be transferred to the behaviour of elementary particles, which will happen in the next book
  - Observer Dependency can now be understood without any knowledge of mathematics
  - The student has to apply critical and active learning, and has to draw conclusions on his own
  - The student will receive feedback on his own conclusions in the next book
- Practice
  - The student already has to apply active learning
- Feedback
  - In the next room is a chest with a book
  - (Beginning of book)
  - The book states the difference between the two blocks
    - \* The left block is static and doesn't change
    - \* The right block changes its block type when observed from different sides
    - \* A block type is a property of blocks in Minecraft
    - \* This is called an Observer Dependent Block
  - Elementary particles also have properties which change when observed
  - However, elementary particles do not change based on the way of observation, which will become clear in the next branch

## Quantum Blocks and Random Collapse

- Information and examples
  - A message appears in the message system, telling the student to find the difference between the two blocks in front of him
  - The left block is an Observer Dependent Block
    - \* If the block is observed from the back-to-front axis, the block has a diamond block type
    - \* If the block is observed from the perpendicular axis, the block has a redstone block type
  - The right block is Quantum Block

- \* If the block is observed, its block type has 50% chance of collapsing to a diamond block type and 50% chance of collapsing to a redstone block type
- At the end of the room is a iron door, which opens up if the Observer Dependent Block and the Quantum Block have resolved to a redstone block type at least once
- Focus attention
  - By comparing the two blocks, the student finds the difference in behaviour between the two blocks
  - This leads to an understanding of the behaviour of Quantum Blocks
  - This gives way to teach the student about the random collapse of elementary particles
- Learning strategies
  - The Quantum Block visualises the behaviour of elementary particles without oversimplifying it
  - The behaviour still has to be linked to the term random collapse, which will happen in the next book
  - The behaviour still has to be transferred to the behaviour of elementary particles, which will happen in the next book
  - Random collapse can now be understood with only a very basic knowledge of mathematics
  - The student has to apply critical and active learning, and has to draw conclusions on his own
  - The student will receive feedback on his own conclusions in the next book
- Practice
  - The student already has to apply active learning
- Feedback
  - In the next room is a chest with a book
  - (Beginning of book)
  - The book states the difference between the two blocks
    - \* The left block is an Observer Dependent Block, similar to the one in the previous branch
    - \* The block type of the right block randomly changes into one of two states when observed
    - \* This is called a Quantum Block
  - The properties of elementary particles also collapse to a random state when observed
  - Scientists are still puzzled by this, which will be elaborated later

## Entanglement (Concept)

- Information and examples
  - A message appears in the message system, telling the student to find the difference between the two groups of blocks in front of him
  - The left group of blocks consists out of independent Quantum Blocks
  - The right group of blocks consists out of entangled Quantum Blocks
  - At the end of the room is a iron door, which opens up if all of the blocks have resolved to a redstone block type at least once
- Focus attention

- By comparing the two groups of blocks, the student finds the difference in behaviour between the two groups of blocks
- This leads to an understanding of the behaviour of entangled Quantum Blocks
- This gives way to teach the student about entangled elementary particles
- Learning strategies
  - The entangled Quantum Blocks visualise the behaviour of boson entangled elementary particles without oversimplifying it
  - The behaviour still has to be linked to the term entanglement, which will happen in the next book
  - The behaviour still has to be transferred to the behaviour of elementary particles, which will happen in the next book
  - Entanglement can now be understood with only a very basic knowledge of mathematics
  - The student has to apply critical and active learning, and has to draw conclusions on his own
  - The student will receive feedback on his own conclusions in the next book
- Practice
  - The student already has to apply active learning
- Feedback
  - In the next room is a chest with a book
  - (Beginning of book)
  - The book states the difference between the two blocks
    - \* The left blocks are independent Quantum Blocks, similar to the one in the previous branch
    - \* The block type of the right blocks always collapse to the same state on observation
    - \* This interdependency between blocks is called Entanglement
  - The properties of an entangled elementary particle also collapses to a state correlating with the collapse of the other particle in the entanglement
  - The properties can always collapse to the same state, this is called boson entanglement
  - The properties can also always collapse to each others opposite state, this is called fermion entanglement
  - Entanglement works no matter the distance between the two particles
  - Entanglement works no matter when the observation of each particle has taken place

## qCraft tutorial

- Quantum Goggles
  - Diverse Quantum Blocks hidden within the decorations of the room
  - An item frame holding Quantum Goggles
  - An item frame holding a book
    - \* With Quantum Goggles, qCraft blocks become fluorescent green
    - \* Equip the goggles by putting the goggles in the head slot within the inventory
- Anti-Observation Goggles

- Diverse Quantum Blocks hidden within the decorations of the room
- An item frame holding Anti-Observation Goggles
- An item frame holding a book
  - \* With Anti-Observation Goggles, the student doesn't trigger any observations on qCraft blocks
- Quantum Resetter
  - An Automatic Observer attached to a Quantum Block, which can be activated by a button
  - A book
    - \* The name of the Automatic Observer
    - \* The Automatic Observer makes an observation on a block when powered
    - \* In real life, the effects of elementary particles can only be indirectly observed by using complex instruments, because these particles are very small

## Realism and Ontology, Superposition (Concept)

- Information and examples
  - On the left are pictures of Einstein, Podolsky and Rosen
  - On the right are pictures of Bohr, Heisenberg and Bell
  - A chest with a book
  - (Beginning of book)
  - Scientists could not find explanations for the phenomena occurring within quantum mechanics
    - \* The fact that mere observations influence the behaviour of quantum particles was found to be very strange
    - \* No factors influencing the collapse of a property could be found
    - \* Scientists also wondered in what state a particle would be in before measurement
  - The early interpretation of quantum mechanics was the Realist interpretation
    - \* Famous realists are displayed on the left wall
    - \* They believed that there were underlying explanations for the phenomena, only the technology needed for measuring these explanations is not available yet
  - The other interpretation was the Ontologist interpretation
    - \* Famous ontologists are displayed on the right wall
    - \* They believed that there were no underlying explanations, but that the phenomena occurred on their own
- Focus attention
  - The student is now asked what he thinks is more likely to be true
  - This way he is triggered to form his own conclusions based on what he knows from physics taught earlier
- Learning strategies
  - The language of physics is used
  - The student connects the different phenomena together to form his conclusions, and also connects them to what he previously learned about quantum mechanics

- The student is triggered to become aware of their realist or deterministic models of physics
- The critical thinking skills of the student are activated
- The student still needs to get feedback on the conclusions the student draws
- Practice
  - The student is now asked whether he tried using the Anti-Observation Goggles when deactivating the Automatic Observer
  - If he did not, he can still try it in the room on the right
- Feedback
  - By activating the quantum resetter with the Anti-Observation Goggles, the student will find that its block type does not collapse to a certain state
  - Instead, the block type will remain in the green "in-between" state
  - The book tells the student that this state is called Superposition
  - When a property of an elementary particle is in superposition, it is in all possible states at the same time
  - The property is in superposition until it is observed and collapses into one of the state
  - The student is now asked to reconsider the earlier question about realism and ontology
  - Superposition is a concept leaning to the ontology camp
  - Most scientists nowadays follow the ontologist interpretation of quantum mechanics

## Uncertainty Principle of Heisenberg (Principle)

- Information and examples
  - Within the room, there are a couple of pictures
  - One picture displays Heisenberg
  - The other pictures display mathematical symbols, with signs below the pictures indicating the meaning of the symbol
    - \* The uncertainty principle of Heisenberg
    - \*  $\sigma x$  (The uncertainty in location)
    - \*  $\sigma p$  (The uncertainty in momentum)
    - \*  $\geq$  (Greater or equal than)
    - \*  $\hbar$  (The reduced Planck constant,  $1.0 \cdot 10^{-34}$ )
  - A book in a chest
- Focus attention
  - (Beginning of book)
  - The formula is called the Uncertainty Principle of Heisenberg
- Learning strategies
  - By using the exact principle, no simplifications take place. Furthermore, the Rutherford-Bohr model of the Atom gets extra clarification
  - The principle is referred to by its name, so again the language of physics is used to relate the principle to a real term
  - The principle is connected to the concept of superposition

- The principle demonstrates an important property of elementary particles
- From a mathematical perspective, the principle is quite accessible considered that the learner is a physics student from secondary education, and no complex or obscure mathematical skills are needed to comprehend the principle
- The student is triggered to think critical about the meaning of the principle and about the interpretation of the principle
- The student is provided with feedback containing the correct information
- Practice
  - The student has to look around and try to make sense of each of the symbols within the formula
- Feedback
  - The product of the uncertainty in momentum and the uncertainty in location has to be greater or equal than the reduced Planck constant divided by 2
  - The book explains every symbol
    - \* The reduced Planck constant  $\hbar$  is a tiny number,  $1.0 \cdot 10^{-34}$
    - \* The  $\geq$  symbol means greater than or equal to
    - \* The part before this symbol has to be greater than or equal to the reduced Planck constant divided by two
    - \* This part exists out of  $\sigma_x$  and  $\sigma_p$
    - \*  $\sigma_x$  is the uncertainty in location
    - \*  $\sigma_p$  is the uncertainty in momentum
    - \* Momentum is closely related to speed
    - \*  $\sigma_x \cdot \sigma_p$  is the product of the uncertainty in location and uncertainty in momentum
  - There are two main implications which follow from the uncertainty principle
    - \* Neither the uncertainty in location nor the uncertainty in momentum can be zero, which means that neither can be known exactly
    - \* This follows from the fact that if either of those are 0, the product is also zero, which would contradict with the fact that it has to be greater than or equal to  $\frac{\hbar}{2}$
    - \* The smaller the uncertainty in location is, the greater the uncertainty in momentum has to be and vice versa
    - \* This follows from the fact that the smaller one of the uncertainties is, the smaller the product of the uncertainties becomes and thus the greater the other uncertainty has to become to compensate, otherwise the product becomes smaller than  $\frac{\hbar}{2}$
  - The student is asked what the realist and what the ontologist interpretation of this principle would be
    - \* A realist would believe that the particle would have a specific location or momentum, but that the needed technology to measure them is not available yet
    - \* An ontologist would believe that the particle has no exact location or momentum, but that they are in a state of superposition
  - The scale in which the uncertainty principle is significant is the scale of the shell of an atom
    - \* The width of the shell varies from 0.1 nm to 0.5 nm
    - \* It means that the exact location of an electron within the shell is not known, but that it is a superposition of all possible locations of the shell
    - \* This is different from for example the location of a planet within orbit around the sun, for its location can be determined quite precise because of the difference in scale
    - \* (End of book)

## Quantum Teleportation (Procedure)

- Information and examples
  - There is a big contraption in the room, displaying the quantum teleportation experiment
    - \* The experiment is divided by a wall in the middle
    - \* The right hand of the room is indicated to be laboratory A and the left hand is indicated to be laboratory B
    - \* In laboratory A, there are two entangled Quantum Blocks
    - \* From these blocks, a signal travels to the wall in the middle
    - \* Mounted in the wall, there is a lamp which has a sign saying "Boson entanglement" and a sign saying "Fermion entanglement"
    - \* In laboratory B, there is one Quantum Block which is also entangled to the Quantum Blocks in laboratory A
    - \* Furthermore, there is a button with a sign saying "Reset experiment", which resets all the Quantum Blocks and activating the "Boson entanglement" lamp
  - A book in a chest
  - (Beginning of book)
  - Science fiction teleportation
    - \* The goal of science fiction is to transport an object from location A to location B
    - \* The object is scanned at location A in order to obtain all information from the particles within the object
    - \* This information is send to location B
    - \* The object is recreated at location B with the information about the particles
    - \* The object at location A is destroyed
    - \* This is not possible because of the uncertainty principle of Heisenberg
  - Quantum teleportation
    - \* The goal of the teleportation is to transfer information from Laboratory A to Laboratory B
    - \* Laboratory A has two particles, and Laboratory B has one particle
    - \* All of these particles are entangled with each other
    - \* The researcher of laboratory A measures the type of entanglement between the two particles
    - \* This information is sent to Laboratory B by means of a classical communication channel
    - \* The researcher in Laboratory B now observes his particle and combines the data received from laboratory A to determine the state of the particle in Laboratory A
    - \* He sends this determination to Laboratory A via the classical communication channel
    - \* She verifies the data to see whether the experiment was successful
- Practice
  - The student is now asked to conduct the steps of Laboratory B in the next room
  - (End of book)
    - \* This room is indicated to be Laboratory B
    - \* In the wall are two lamps, again these are indicated as either "Boson entanglement" or "Fermion entanglement"
    - \* There is a Quantum Block in the room

- \* There is a button panel in the room, with which the student has to indicate what the particle in Laboratory A should be
- \* There is a button which resets the experiment
- \* There is a closed iron door at the end of the room
- The student has to look at the type of entanglement, combine that with the state of the Quantum Block and has to press the right button in order to progress through the next room
- Feedback
  - The feedback is provided by the iron door opening if the student has selected the right button
- Focus attention
  - A chest with a book
  - (Beginning of book)
  - The student is asked whether quantum teleportation could be used in order to communicate instantly between two locations
  - This is not possible for two reasons
    - \* The collapse of the property of an elementary particle cannot be influenced, and therefore it is not possible to encode a message
    - \* The type of entanglement still has to be transmitted via a classical communication channel
  - (End of book)
- Learning strategies
  - The science fiction teleportation is displayed, because this is the portrayal of teleportation the student probably knows
  - The teleportation experiment had to be simplified in order for it to be able being displayed within qCraft. However, on a conceptual level it still is a legitimate representation of a real quantum teleportation, so it is still not misleading to the student
  - All the correct terms are applied in the texts
  - This experiment finally combines most of the concepts within this instruction together
  - The text displays how the teleportation conducted by the student connects to the real world
  - The teleportation experiment requires no new mathematical skills
  - The student is actively engaged by having to conduct a part the teleportation himself
  - The student is triggered to think critically about the teleportation by having to apply it to the possibility of instantaneous communication

## Conclusion

- Summary and review
  - The student arrives in the office of professor qCraft
  - The professor tells the student what he has learned about quantum mechanics by using the teleportation experiment
  - He had to understand elementary particles, because these contain the information he wanted to teleport

- He had to understand observer dependency and to understand the ontological interpretation to know that the information would become defined on observation, which is the active step of teleportation
- He had to understand that particles collapse to a random state to know what information he would be teleporting
- He had to understand Quantum Entanglement, because this is the main concept quantum teleportation relies on
- He had to understand classical communication to know why communication cannot take place instantly
- He had to understand the Heisenberg Uncertainty Principle to know that the science fiction teleportation cannot take place

- Transfer

- The professor also states that there is a lot more to learn in the area of quantum mechanics
- The students could take a look at fundamental experiments which has shaped our view of quantum mechanics, like the double-slit experiment or the EPR experiment
- The student could also learn more by looking at famous debates by famous scientists
- Finally, the student could get skills in the mathematical side of quantum mechanics
- But at least the student should now have an understanding about the fundamental concepts of quantum mechanics

- Closure

- The professor adds to this that quantum mechanics is very relevant in modern technology, he mentions the laser and the transistor as examples, and he also mentions that quantum computers could be a very relevant topic in the future
- Finally, he says to the student that he can now go back to the real world, and he thanks the student for his participation

# Framework for the Second Version of the Quantum Teleportation Experiment

- Book 1
  - Everything learned can be combined in this branch
  - The experiment in Minecraft a simplified version from real quantum teleportation
  - The goal of science fiction is to transport an object from location A to location B
  - The object is scanned at location A in order to obtain all information from the particles within the object
  - This information is send to location B
  - The object is recreated at location B with the information about the particles
  - The object at location A is destroyed
  - This is not possible because of the uncertainty principle of Heisenberg
  - In the next room the student will conduct quantum teleportation
- Book 2
  - Quantum teleportation is sending information instantaneously from one location to another location
  - This will be done by using entanglement
  - Information will be teleported from laboratory A to laboratory B
  - Two entangled particles will be used, particle A and particle B
  - Particle A is in laboratory A and particle B is in laboratory B
  - Information will be teleported from particle A to particle B
  - Until now, states of Quantum Blocks could be directly observed
  - Reminder: For elementary particles this is not possible
  - The combined energy levels of two entanglement can be measured
  - With the combined energy levels, the type of entanglement can be determined
  - Reminder: Bosons collapse to the same state and Fermions collapse to the other state
  - Particle A and B are at different location, therefore the combined energy levels cannot be measured
  - A third particle is added, particle X
  - Particle X is entangled with particle A, and by this particle X gets the same state as particle B
  - Now, the combined energy levels of particle A and X are measured
  - The results of this measurement is now transmitted to laboratory B using a classical communication channel

- The student is now asked to conduct three successful teleportations in a row within a simulation of laboratory A
- The student has to determine the type of entanglement based on the states of two Quantum Blocks
- The student has to send this information using one of two buttons labeled "Boson" and "Fermion"
- Above the buttons are three lamps
- Every time the student hits the right button, a new lamp will be activated
- When the last lamp is activated, an iron door will open, allowing the student to move to the next room
- Book 3
  - These are the steps the researcher at laboratory B has to perform
  - The researcher at laboratory B measures the energy level of particle B before the information about the results from laboratory A
  - Reminder, particle B has the same state as particle X
  - Together with the energy level of particle B and the results from laboratory A the researcher can now determine the state of particle A
  - This information is transmitted back to laboratory A using the classical communication channel
  - The findings are verified at laboratory A
  - The student is now asked to conduct three successful teleportations in a row within a simulation of laboratory B
  - The student has to determine the state of Quantum Block A based on the state of Quantum Block B and the type of entanglement, indicated by two lamps labeled "Boson" and "Fermion"
  - The student has to send this information using one of two buttons labeled "Blue block" and "Red block"
  - Above the buttons are three lamps
  - Every time the student hits the right button, a new lamp will be activated
  - When the last lamp is activated, an iron door will open, allowing the student to move to the next room
- Book 4
  - The student is asked whether quantum teleportation can be used to communicate instantaneously from one location to another
  - It cannot be used for communication
    - \* The collapse of the property of an elementary particle cannot be influenced, and therefore it is not possible to encode a message
    - \* The type of entanglement still has to be transmitted via a classical communication channel

# Final Framework

## Minecraft Tutorial

- Moving
  - A sign telling the student to look around by using the mouse
  - A sign on the other side telling the student to move around by using the WASD keys
- Jumping
  - A sign telling the student to use the spacebar to jump
  - One horizontal bar of one block high forcing the student to jump over it in order to progress
  - One vertical gap of one block high forcing the student to jump over it in order to progress
- Interaction
  - A sign telling the student to use the right mouse button in order to interact with objects
  - A lever connected to a redstone lamp
  - A button connected to a redstone lamp
  - An iron door at the end, preventing the student from continuing until he has activated every redstone lamp at least once
- Inventory
  - A sign telling the student to use the E key in order his inventory
  - A chest containing a paper named "ticket"
  - An iron door at the end preventing the student from continuing
  - A dropper in which the ticket can be inserted, upon which the iron door opens
- Use items and read books
  - A sign telling the student to use the right mouse button in order to activate items in his inventory
  - A book in a chest
  - A button at the end of the room, teleporting the student to the qCraft museum

## Introduction

- Attention
  - (Beginning of book)
  - It welcomes the student to Minecraft

- The writer introduces himself as Professor qCraft
- Purpose
  - The professor wants to show the student his work on Quantum Blocks
  - The professor mentions different concepts of quantum mechanics:
    - \* Superposition
    - \* Entanglement
    - \* Quantum Teleportation
- Interest or Motivation
  - The professor is trapped within his office, and the student has to rescue him
  - The professor has a communication system available, so he can guide the student
  - (End of book)
- Preview
  - The student teleports to the qCraft museum
  - This is a big hallway with closed iron doors at both sides
  - Every door has a dropper next to it, indicated by a sign saying "Ticket"
  - The doors have signs in front of them which indicate the topic beyond that door:
    - \* The Microscopic World
    - \* Theory of Relativity
    - \* Observer Dependency
    - \* Quantum Blocks
    - \* Entanglement
    - \* Tutorial II
    - \* Realism and Ontology
    - \* The Uncertainty Principle of Heisenberg
    - \* Teleportation
    - \* Office of Professor qCraft
  - When teleporting to the museum, the student received a paper with the name "The Microscopic World"
  - Upon putting this paper into the dropper of the first door, the corresponding iron door opens up
  - Behind the iron door is a button which teleports the student to the next branch

## Body

### The Rutherford-Bohr Model of the Atom and Elementary Particles (Concept)

- A chest with a book
- Two pictures on the wall:
  - A picture of Niels Bohr
  - A picture of the Rutherford-Bohr Model of the Atom similar to figure 8 on page 79
- Book

- Everything around us exists out of molecules
  - Molecules exist out of atoms
  - Atoms are made out of a core, the nucleus, and a shell, the electrons
  - The nucleus of an atom exists out of protons and neutrons
  - The electrons stay in the shell of an atom, because electrons and protons are attracted to each other
  - At this point the book refers to a picture shown on a wall, which depicts the Rutherford-Bohr Atom Model
  - This attraction is caused by electrons having a negative charge and protons having a positive charge
  - Neutrons do not have any charge
  - There are other nanoscopic particles, a very famous one is the photon
  - The photon is known as the light particle
  - A proton or a neutron consists out of three quarks
  - Quarks, electrons and photons are considered to be elementary particles
  - An elementary particle is a particle of which we don't know its substructure
  - This means that we don't know what the elementary particles are composed of
  - The book emphasises that it is sufficient to know that elementary particles exist, and that these are the particles which demonstrate quantum behaviour
- After reading the book, the student has to go through a multiple choice test
    - An atom consists out of:
      - \* A nucleus and shell (correct)
      - \* Photons
    - The shell of an atom consists out of:
      - \* Photons
      - \* Neutrons
      - \* Electrons (correct)
      - \* Quarks
    - The nucleus of an atom consists out of:
      - \* Molecules
      - \* Protons ad Neutrons (correct)
      - \* Electrons
      - \* It is an elementary particle
    - Select all the particles that we consider to be elementary particles:
      - \* Photons (correct)
      - \* Atoms
      - \* Electrons (correct)
      - \* Protons
      - \* Neutrons
      - \* Quarks (correct)
    - The test is represented by a long hallway with closed iron doors
    - Between the iron doors are buttons or levers with signs depicting the multiple choice answers, of which the correct ones open the next door

- The question is displayed on a sign in the beginning of the room
- At the end of each branch is a chest with the ticket to the next branch. When the student has taken the ticket, he is teleported back into the museum

## Observer Dependency

- A big room with a square gap in the middle, also displayed in figure 11 at page 124.
- Within the gap are two pedestals with 8 evenly spaced blocks on top of them
- The left blocks are static blocks with the diamond block type
- These blocks are indicated to be "Normal Blocks" by a sign on the pedestal
- The right blocks are Observer Dependent Blocks
  - If a block is observed from the back-to-front axis, the block has a diamond block type
  - If a block is observed from the perpendicular axis, the block has a redstone block type
- These blocks are indicated to be "New Blocks" by a sign on the pedestal
- Around the gap is a catwalk
- Within the corners of the gap are pillars which reach towards the ceiling
- At the students side is a stair which can be used to get up the walkway again in case the student fell into the gap
- At the other side of the room there is a hallway
- At the left and right side of the room are closed iron doors
- The student can progress through the hallway
- Book 1
  - The student is asked whether he has seen the "New Blocks" change their colour
  - These blocks are special blocks
  - In the next room are Quantum Goggles
  - With these goggles, the special blocks will appear as being fluorescent green
- The student progresses through a hallway at the right
- In the next room the student finds a pillar with an item frame containing the Quantum Goggles
- There are a couple of Observer Dependent Blocks in the room
- The student progresses through a hallway at the right
- Book 2
  - The student will go to the first room again
  - The student is now asked to find the difference in behaviour between the normal blocks and the new blocks
- At the right of the room, there is the iron door seen earlier in the first room

- Next to the door is a lever, which opens this iron door as well as the other iron door from the first room
- Now the student is in the first room again
- Progression is through the other iron door
- Book 3
  - The normal blocks never change and are always predictable
  - The new blocks change when observed from different sides
  - This block is called an Observer Dependent Block
  - The block stays the same block, it just takes on different values for the block-type property
  - The student has to use this mechanic to solve the puzzle in the next room
- See figure 12 on page 125
- At the left side of the room an iron door is blocking the student from progressing
- There is a wall coming from the opposite of the room to just before the middle, leaving a way to the other side before the wall
- At the opposite side left from the wall is an Observer Dependent Block, which block type collapses to redstone when observed from all sides except for the side opposite of the iron door, at which it collapses to diamond
- If the Observer Dependent Block is a diamond block, the iron door opens up and the student can advance
- Book 4
  - Minecraft blocks have properties which define them
  - Elementary also have such properties
  - Examples of such properties are polarisation, spin or charge
  - Observer Dependency is the fact that if a property of an elementary particle is observed, the property collapses to a certain value
  - In the next branch the student will learn more about the exact behaviour of elementary particles

## Quantum Blocks

- The first room is very similar to the first room of the previous branch, also displayed in figure 11 at page 124, except for the fact that:
  - There is a sign at the beginning of the room asking the student of finding the difference in behaviour between the two groups of blocks
  - There are no doors at the left and right side
  - The left group of blocks now consists out of the same Observer Dependent Blocks as the Observer Dependent Blocks from the previous branch
  - The "Normal Blocks" sign is now replaced by an "Observer Dependent Blocks" sign
  - The right group of blocks now consists out of Quantum Blocks, of which the block type has a 50% chance of collapsing to diamond block type and a 50% chance of collapsing to a redstone block type

- It is possible to traverse to the next room
- Book 1
  - The new blocks might have changed their block types more often than the Observer Dependent Blocks
  - The new blocks are called Quantum Blocks
  - Every time a Quantum Block is observed its block type collapses to one of two states decided by random
  - The concept of Observer Dependency demonstrates itself by the fact that the change of block type of a Quantum Block triggers by the observation of a student
- The next room is a puzzle room, see figure 13 on page 125
- There are two Quantum Blocks
- There are two glass pane walls with iron doors
- Each Quantum Block is connected with an iron door
- If the block type of the Quantum Block is the diamond block type, the door is open
- If the block type of the Quantum Block is the redstone block type, the door is closed
- In the next room is an Quantum Resetter attached to a Quantum Block, which can be activated by a button
- There is also a chest with book 3
  - The grey contraption is called a Quantum Resetter
  - It resets the block type of a Quantum Block
  - This can be used to not have to look away in order trigger a new observation on a Quantum Block
- In the next room, there are 4 of the Quantum Resetter set ups from the previous room
- There is an iron door at the end of the room
- If all the Quantum Blocks in the room have the diamond block type the iron door opens and the student can proceed to the next room
- Book 3
  - The behaviour of Quantum Blocks is very similar to that of Elementary Particles
  - Elementary Particles also have properties which on observation collapse to one of the possible states at random
  - Elementary Particles are too small to observe directly, but their properties can still be measures by using certain instruments

## Realism and Ontology, Superposition (Concept)

- On the left are pictures of Einstein, Podolsky and Rosen
- On the right are pictures of Bohr, Heisenberg and Bell
- A chest with a book
- (Beginning of book)
- Scientists could not find explanations for the phenomena occurring within quantum mechanics
  - The fact that mere observations influence the behaviour of quantum particles was found to be very strange
  - No factors influencing the collapse of a property could be found
  - Scientists also wondered in what state a particle would be in before measurement
- The early interpretation of quantum mechanics was the Realist interpretation
  - Famous realists are displayed on the left wall
  - They believed that there were underlying explanations for the phenomena, only the technology needed for measuring these explanations is not available yet
- The other interpretation was the Ontologist interpretation
  - Famous ontologists are displayed on the right wall
  - They believed that there were no underlying explanations, but that the phenomena occurred on their own
- The student is now asked what he thinks is more likely to be true
- This way he is triggered to form his own conclusions based on what he knows from physics taught earlier

## Superposition

- A couple of Quantum Blocks are in the room
- A pillar with an item frame containing Anti-Observation Goggles and an item frame containing book 1
  - The goggles are Anti-Observation Goggles
  - With the goggles the student will not trigger any observation on Quantum Blocks
  - This prevents Quantum Blocks to collapse
- A button on the other side of the room teleporting the student to a puzzle, displayed on figure 14 on page 126
  - A room with a vertical gap from left to right
  - A bridge of Quantum Blocks in Superposition in the middle
  - The bridge starts at the left side of the gap, goes to the right side and then back to the left side, where the student can reach the other platform
  - The block type of the Quantum Blocks can collapse to either quartz blocks or to gravel blocks
  - Gravel blocks will fall down
  - A button at the starting platform resets the puzzle

- A button at the end teleports the student to the next room
- A Quantum Resetter attached to a Quantum Block, which can be activated by a button
- A book with a chest
  - The student is asked to wear the Anti-Observer Goggles and then trigger the Quantum Resetter
  - By activating the Quantum Resetter with the Anti-Observation Goggles, the student will find that its block type does not collapse to a certain state
  - Instead, the block type will remain in the green "in-between" state
  - The book tells the student that this state is called Superposition
  - When a property of an elementary particle is in superposition, it is in all possible states at the same time
  - The property is in superposition until it is observed and collapses into one of the state
  - The student is now asked to reconsider the earlier question about realism and ontology
  - Superposition is a concept leaning to the ontology camp
  - Most scientists nowadays follow the ontologist interpretation of quantum mechanics

### Uncertainty Principle of Heisenberg (Principle)

- Within the room, there are a couple of pictures
- One picture displays Heisenberg
- The other pictures display mathematical symbols, with signs below the pictures indicating the meaning of the symbol
  - The uncertainty principle of Heisenberg
  - $\sigma x$  (The uncertainty in location)
  - $\sigma p$  (The uncertainty in momentum)
  - $\geq$  (Greater or equal than)
  - $\hbar$  (The reduced Planck constant,  $1.0 \cdot 10^{-34}$ )
- A book in a chest
  - The formula is called the Uncertainty Principle of Heisenberg
  - By using the exact principle, no simplifications take place. Furthermore, the Rutherford-Bohr model of the Atom gets extra clarification
  - The principle is referred to by its name, so again the language of physics is used to relate the principle to a real term
  - The principle is connected to the concept of superposition
  - The principle demonstrates an important property of elementary particles
  - From a mathematical perspective, the principle is quite accessible considered that the learner is a physics student from secondary education, and no complex or obscure mathematical skills are needed to comprehend the principle
  - The student is triggered to think critical about the meaning of the principle and about the interpretation of the principle
  - The student is provided with feedback containing the correct information

- The student has to look around and try to make sense of each of the symbols within the formula
- The product of the uncertainty in momentum and the uncertainty in location has to be greater or equal than the reduced Planck constant divided by 2
- The book explains every symbol
  - \* The reduced Planck constant  $\hbar$  is a tiny number,  $1.0 \cdot 10^{-34}$
  - \* The  $\geq$  symbol means greater than or equal to
  - \* The part before this symbol has to be greater than or equal to the reduced Planck constant divided by two
  - \* This part exists out of  $\sigma x$  and  $\sigma p$
  - \*  $\sigma x$  is the uncertainty in location
  - \*  $\sigma p$  is the uncertainty in momentum
  - \* Momentum is closely related to speed
  - \*  $\sigma x \cdot \sigma p$  is the product of the uncertainty in location and uncertainty in momentum
- There are two main implications which follow from the uncertainty principle
  - \* Neither the uncertainty in location nor the uncertainty in momentum can be zero, which means that neither can be known exactly
  - \* This follows from the fact that if either of those are 0, the product is also zero, which would contradict with the fact that it has to be greater than or equal to  $\frac{\hbar}{2}$
  - \* The smaller the uncertainty in location is, the greater the uncertainty in momentum has to be and vice versa
  - \* This follows from the fact that the smaller one of the uncertainties is, the smaller the product of the uncertainties becomes and thus the greater the other uncertainty has to become to compensate, otherwise the product becomes smaller than  $\frac{\hbar}{2}$
- The student is asked what the realist and what the ontologist interpretation of this principle would be
  - \* A realist would believe that the particle would have a specific location or momentum, but that the needed technology to measure them is not available yet
  - \* An ontologist would believe that the particle has no exact location or momentum, but that they are in a state of superposition
- The scale in which the uncertainty principle is significant is the scale of the shell of an atom
  - \* The width of the shell varies from 0.1 nm to 0.5 nm
  - \* It means that the exact location of an electron within the shell is not known, but that it is a superposition of all possible locations of the shell
  - \* This is different from for example the location of a planet within orbit around the sun, for its location can be determined quite precise because of the difference in scale

## Classical Communication

- A contraption on the side
  - Two lamps
  - Connected with redstone repeaters
  - Which is connected to a redstone clock
  - Every second the first lamp turns on and off, then a signal travels through the repeaters and finally the second lamp turns on and off
  - When the first lamp turns on a noteblock plays a C

- When the second lamp turns on a noteblock plays a F sharp
- A chest with a book
  - The student probably already knows of Einstein
  - He found that particles have a maximum possible speed
  - This speed is 300 000 000 m/s
  - This is also called light speed, for photons travel constantly at this speed
  - Other particles would need infinite energy to travel with the light speed
  - Small particles can be used to communicate over distances
    - \* Information can be translated to ones and zeroes
    - \* These bits can be translated to a pattern of emitting photons
    - \* These photons travel through a glass fibre cable
    - \* At the other side the pattern of photons can be translated back to information
  - This is called Classical Communication
  - Because of the light speed, Classical Communication cannot take place instantaneously
  - The student is now asked to calculate the minimum time necessary in order to communicate with someone else 3000 km away
- At the end of the room is a sign which asks the student whether the calculation has been performed
- In the next room is a sign which tells the answer (0.01 s)

## Entanglement

- The first room is very similar to the first room of the Quantum Block branch, also displayed in figure 11 at page 124, except for the fact that:
  - The left group of blocks now consists out of the same Quantum Blocks as the Quantum Blocks from the Quantum Blocks branch
  - The "Normal Blocks" sign is now replaced by a "Quantum Blocks" sign
  - The right group of blocks also consists out of the Quantum Blocks, however they are now also entangled
- It is possible to traverse to the next room
- Book 1
  - The Quantum Blocks collapsed to random states independently from each other
  - The New Blocks always collapsed to the same state at the same time
  - This interdependency is called Quantum Entanglement
- In the next room is a puzzle, also displayed in figure 15 on page 126
  - In the room are a couple of Quantum Blocks of which the block type has a 50% chance of collapsing to the diamond block type and 50% to the air block type, which are all entangled with each other
  - At first, the student is blocked by a wall of these Quantum Blocks
  - Then the student is in a room divided by a gap from left to right
  - There is a bridge of the entangled Quantum Blocks

- On the other side the student is again blocked by a wall of the Quantum Blocks
- Book 2
  - Until now, entangled Quantum Blocks always collapsed to the same state
  - In quantum mechanics it is also possible for entangled particles to always collapse to each others opposite state
  - When the entangled particles always collapse to the same state they are called bosons
  - When the entangled particles always collapse to each others opposite state they are called fermions
  - It is not possible on beforehand to know whether particles are bosons or fermions, a measurement of their combined energy levels is needed to determine this
- The student now has to apply the knowledge about bosons and fermions
  - The student has to determine the type of entanglement based on the states of two Quantum Blocks
  - The student has to send this information using one of two buttons labeled "Boson" and "Fermion"
  - Above the buttons are three lamps
  - Every time the student hits the right button, a new lamp will be activated
  - When the last lamp is activated, an iron door will open, allowing the student to move to the next room
- In the next room the student is again asked to apply the knowledge about bosons and fermions
  - The student has to determine the state of Quantum Block A based on the state of Quantum Block B and the type of entanglement, indicated by two lamps labeled "Boson" and "Fermion"
  - The student has to send this information using one of two buttons labeled "Blue block" and "Red block"
  - Above the buttons are three lamps
  - Every time the student hits the right button, a new lamp will be activated
  - When the last lamp is activated, an iron door will open, allowing the student to move to the next room
- Books 3
  - The student is asked whether quantum teleportation can be used to communicate instantaneously from one location to another
  - It cannot be used for communication
    - \* The collapse of the property of an elementary particle cannot be influenced, and therefore it is not possible to encode a message
    - \* The type of entanglement still has to be transmitted via a classical communication channel

## Conclusion

- Summary and review
  - The student arrives in the office of professor qCraft
  - The professor is confined behind a wall with a closed iron door, which can be opened with a lever
  - When the iron door opens, the professor starts talking
  - The professor thanks the student for freeing him
  - The professor now tells the student what he has learned about quantum mechanics
  - He learned about elementary particles
  - He learned about observer dependency
  - He learned that particles collapse to a random state
  - He learned about realism and ontology
  - He learned about Quantum Entanglement
  - He learned about classical communication and why communication cannot take place instantly
  - He learned about the Heisenberg Uncertainty Principle
- Transfer
  - The professor also states that there is a lot more to learn in the area of quantum mechanics
  - The students could take a look at fundamental experiments which has shaped our view of quantum mechanics, like the double-slit experiment or the EPR experiment
  - The student could also learn more by looking at famous debates by famous scientists
  - Finally, the student could get skills in the mathematical side of quantum mechanics
  - But at least the student should now have an understanding about the fundamental concepts of quantum mechanics
- Closure
  - The professor adds to this that quantum mechanics is very relevant in modern technology, he mentions the laser and the transistor as examples, and he also mentions that quantum computers could be a very relevant topic in the future
  - Finally, he says to the student that he can now go back to the real world, and he thanks the student for his participation

# Settings

- gamemode: 2
- commandBlockOutput: false
- doDaylightCycle: false
- doFireTick: false
- doMobSpawning: false
- doTileDrops: false
- keepInventory: true
- naturalGeneration: true

# Floor Plans



Figure 10: The floor legend for the floor plans below

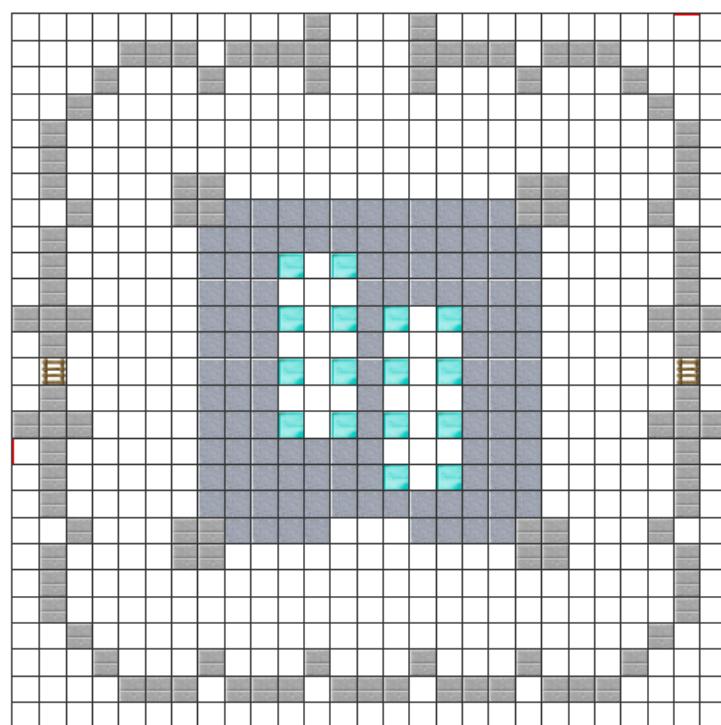


Figure 11: The floor plan for the rooms used to introduce the student to Observer Dependent Blocks, Quantum Blocks and entangled Quantum Blocks. The doors at the left and right side are only there in the Observer Dependency branch

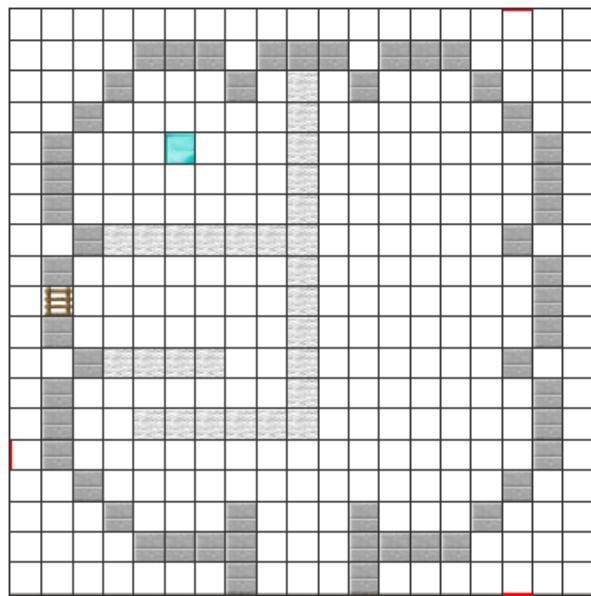


Figure 12: The floor plan of the puzzle within the Observer Dependency branch.

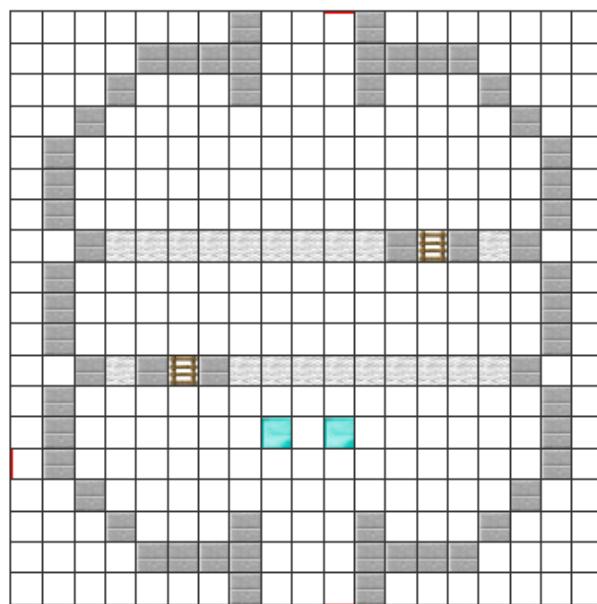


Figure 13: The floor plan of the first puzzle within the Quantum Block branch.

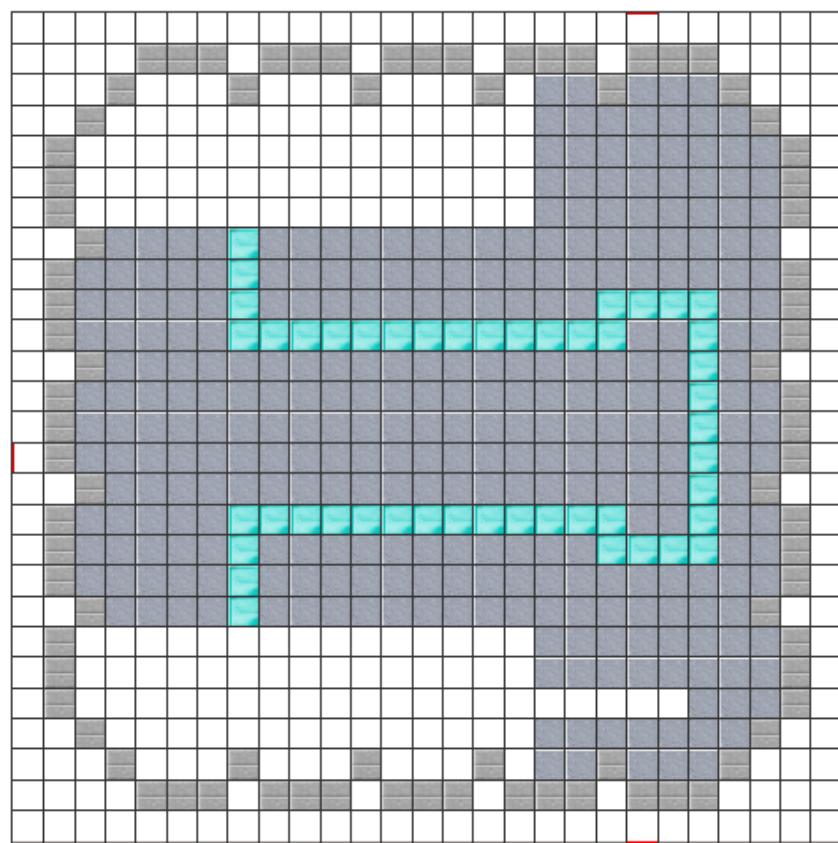


Figure 14: The floor plan of the puzzle within the Superposition branch.

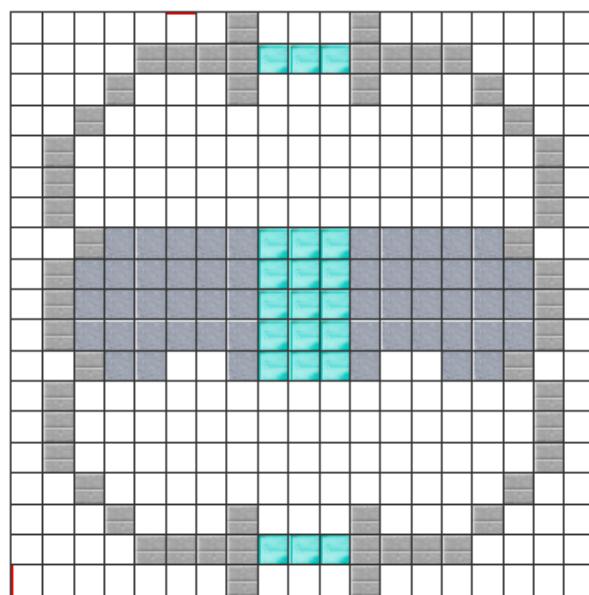
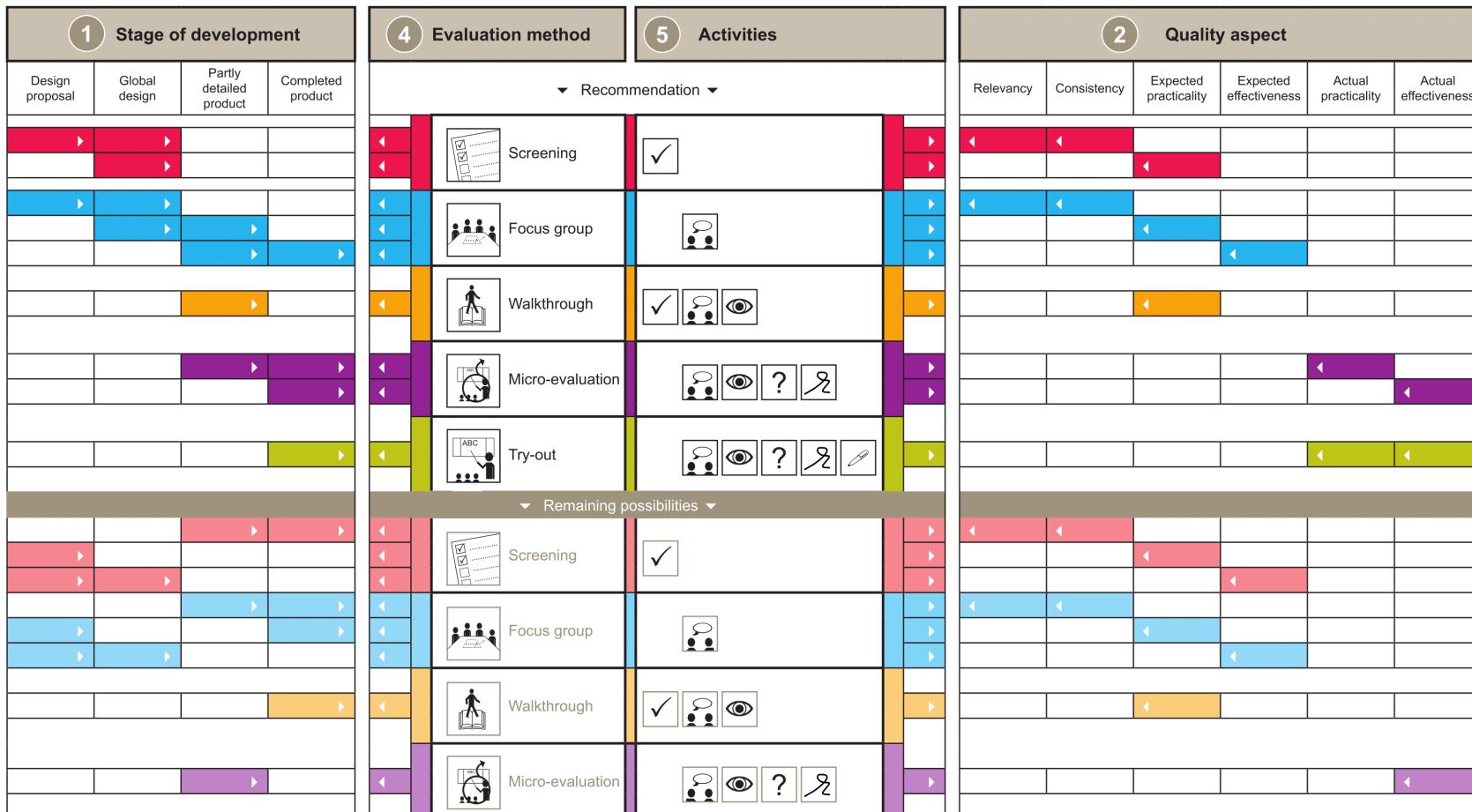


Figure 15: The floor plan of the puzzle within the Entanglement branch.



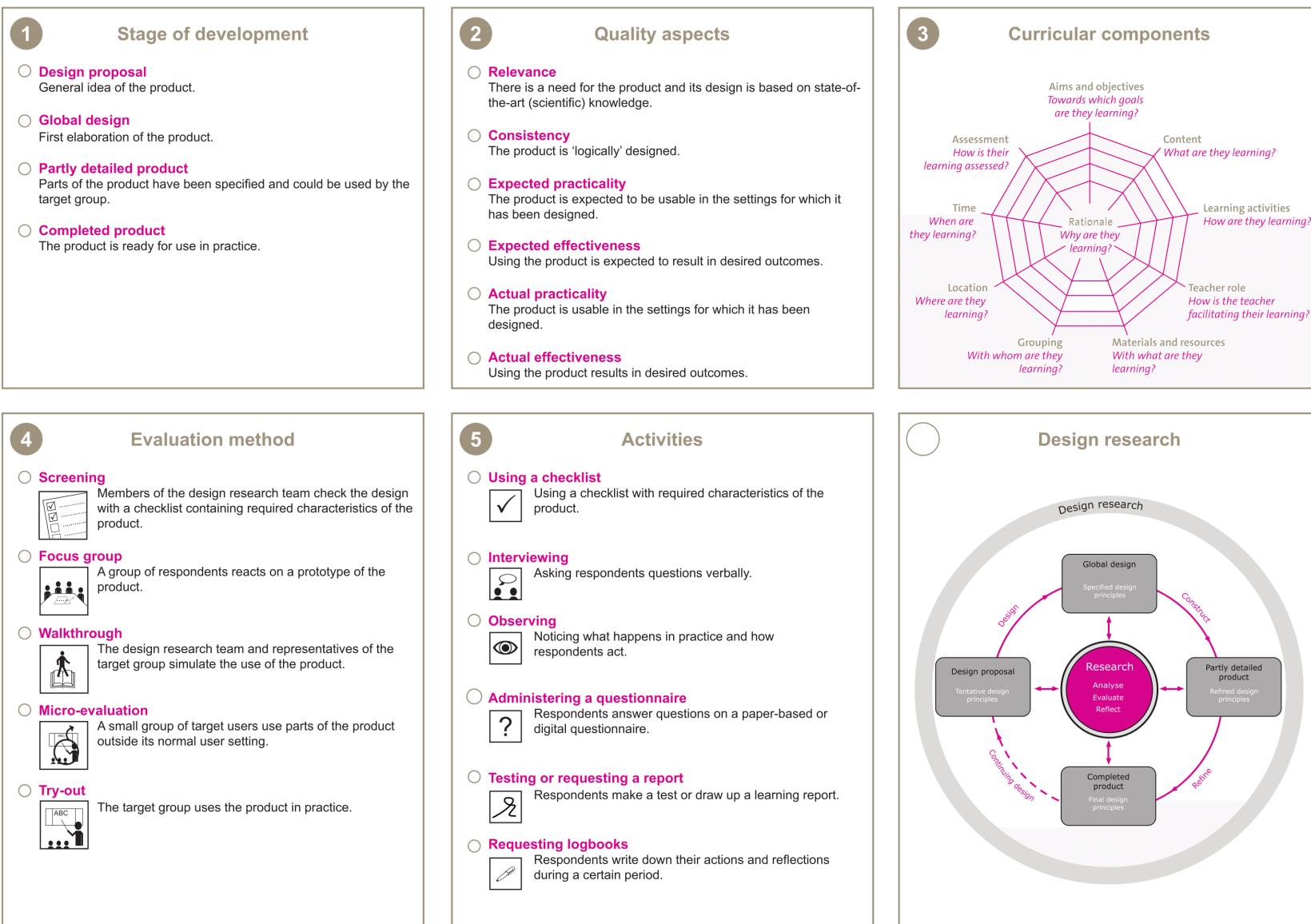
## **‘Evaluation matchboard’**



Explanation: On one horizontal row, combine a stage of development (1) with a quality aspect (2) and find an evaluation method (4) with relevant activities (5)

slo

Nieveen, N., Folmer, E., & Vliegen, S. (2012). *Evaluation Matchboard*. Enschede, the Netherlands: SLO.



# Charts of the Results of the Evaluation

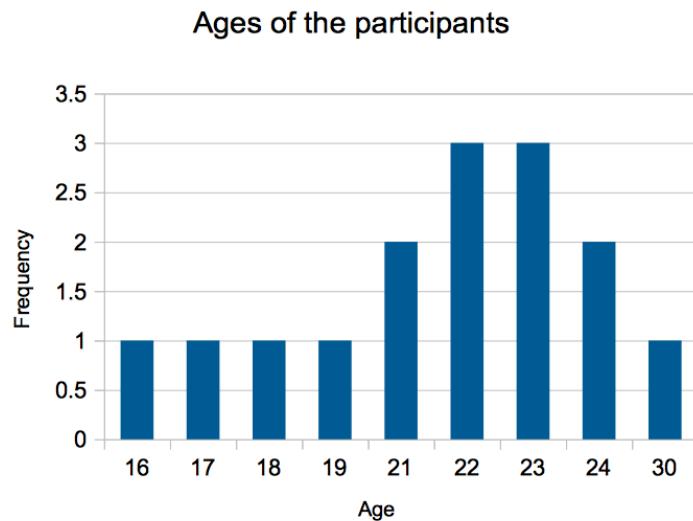


Figure 16: A chart displaying the ages of the respondents.

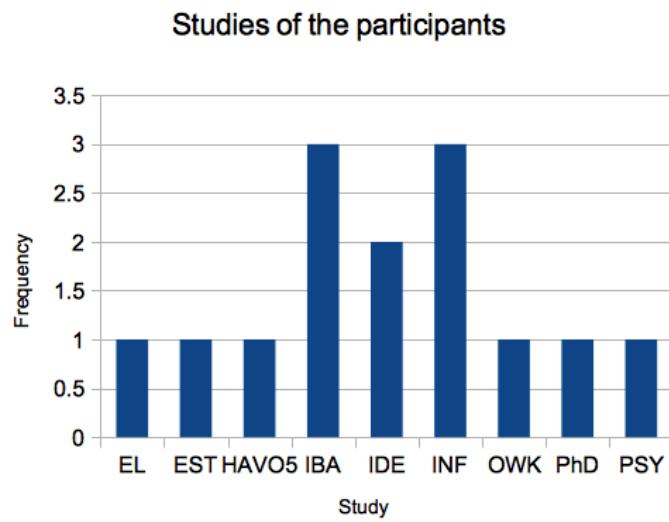


Figure 17: A chart displaying the studies of the respondents.

## Faculties of the Respondents

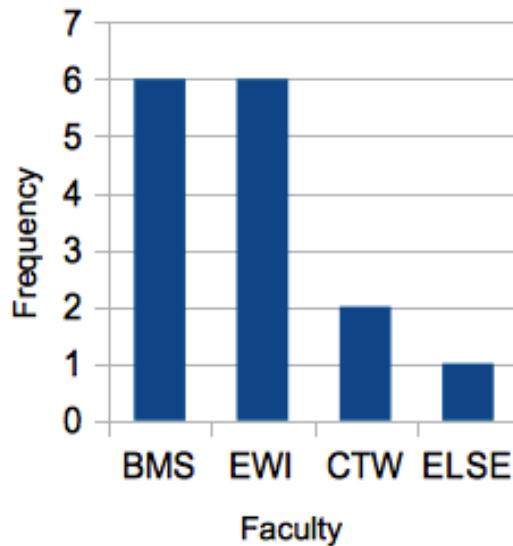


Figure 18: A chart displaying the faculties the respondents are enrolled in.

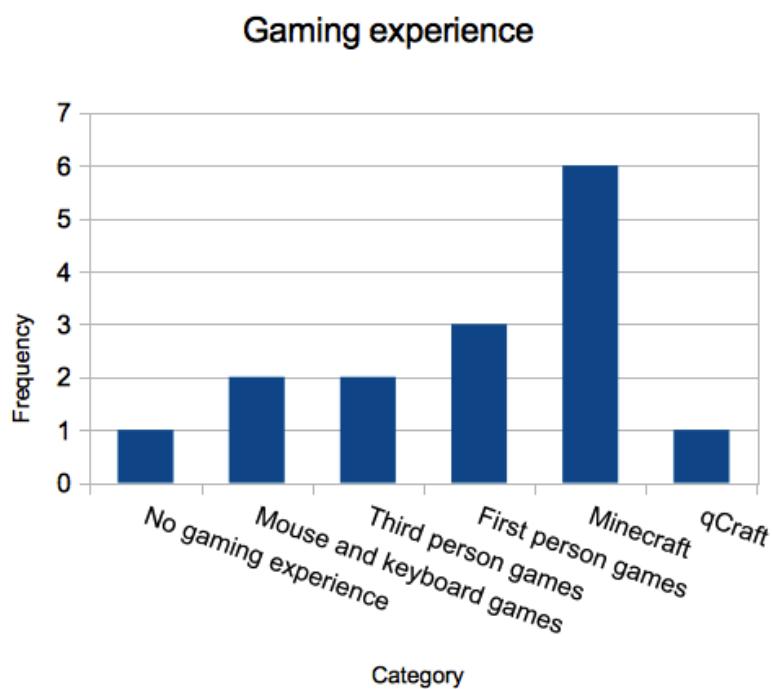


Figure 19: A chart displaying the gaming experience of the respondents.

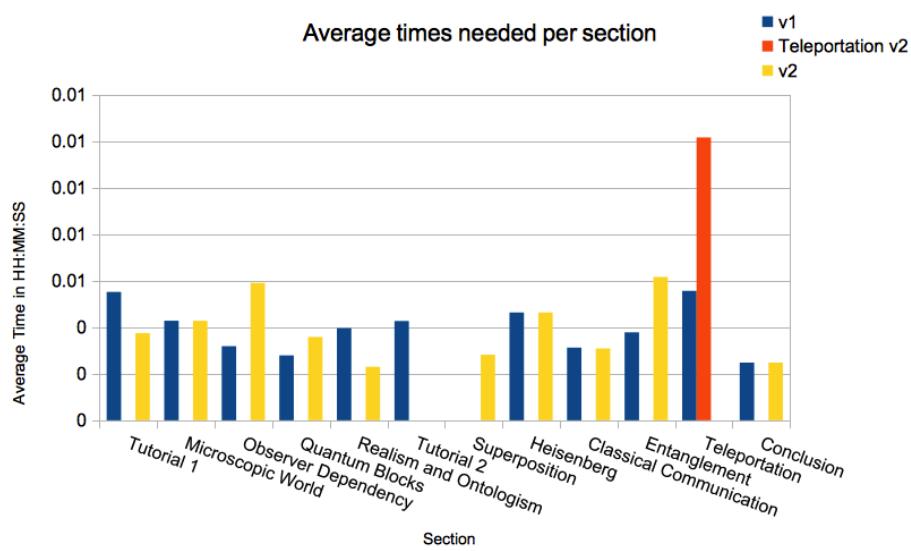


Figure 20: A chart displaying the average times needed for each section of the instruction.

# Amount of Coded Fragments

	NEH	304	305	401	705	NEL	302	502	NCL	404	703	804	PE	205	704	PC	101	204	603	TOTAL:
<b>Reaction</b>	<b>135</b>	<b>38</b>	<b>26</b>	<b>42</b>	<b>29</b>	<b>81</b>	<b>24</b>	<b>57</b>	<b>105</b>	<b>38</b>	<b>39</b>	<b>28</b>	<b>44</b>	<b>12</b>	<b>32</b>	<b>119</b>	<b>74</b>	<b>11</b>	<b>34</b>	<b>484</b>
New information	12	0	0	10	2	10	2	8	5	1	1	3	3	2	1	10	6	1	3	40
Difficulty	27	8	7	9	3	24	10	14	25	14	7	4	5	2	3	3	0	1	2	84
Language	4	1	1	0	2	5	0	5	7	2	2	3	3	1	2	7	3	2	2	26
Use of Minecraft	18	10	1	3	4	4	0	4	11	2	4	5	5	2	3	14	6	1	7	52
Amount of text / gameplay	5	0	1	2	2	4	1	3	6	4	1	1	4	1	3	9	2	2	5	28
Philosophical value	4	0	1	1	2	2	1	1	0	0	1	3	1	2	7	2	2	3	17	
Amusement value	17	10	3	2	2	7	4	3	11	4	6	1	7	2	5	6	3	1	2	48
Topical excitement	14	3	1	6	4	2	1	1	7	1	0	6	3	1	2	5	1	1	3	31
Learning process	20	5	6	7	2	15	5	10	28	7	17	4	8	0	8	15	11	0	4	86
Playing experience	7	1	3	0	3	8	0	8	4	3	1	0	2	0	2	42	39	0	3	63
Relevance	3	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Criticism towards subject	4	0	1	0	3	0	0	0	0	0	0	0	0	1	0	1	1	0	0	6
<b>Learning</b>	<b>102</b>	<b>27</b>	<b>21</b>	<b>28</b>	<b>26</b>	<b>43</b>	<b>16</b>	<b>27</b>	<b>59</b>	<b>5</b>	<b>23</b>	<b>31</b>	<b>19</b>	<b>1</b>	<b>18</b>	<b>20</b>	<b>1</b>	<b>0</b>	<b>19</b>	<b>243</b>
Elementary particle	17	5	3	3	6	9	3	6	16	5	4	7	2	0	2	2	0	0	2	46
Relativity theory / classical communication	12	5	3	1	3	8	5	3	2	0	2	0	1	0	1	2	0	0	2	25
Observer dependency / Superposition	23	6	7	6	4	6	5	1	13	0	4	9	3	0	3	3	0	0	3	48
Realism and Ontology	14	5	2	5	2	6	0	6	5	0	3	2	3	0	3	2	0	0	2	30
Entanglement	17	3	2	7	5	7	1	6	7	0	3	4	3	0	3	3	0	0	3	37
Uncertainty Principle of Heisenberg	10	3	4	0	3	5	2	3	10	0	4	6	4	1	3	5	1	0	4	34
Teleportation	9	0	0	6	3	2	0	2	6	0	3	3	3	0	3	3	0	0	3	23
<b>Suggestions improvement</b>	<b>13</b>	<b>2</b>	<b>6</b>	<b>5</b>	<b>0</b>	<b>10</b>	<b>7</b>	<b>3</b>	<b>9</b>	<b>4</b>	<b>4</b>	<b>1</b>	<b>4</b>	<b>4</b>	<b>0</b>	<b>67</b>	<b>44</b>	<b>14</b>	<b>9</b>	<b>103</b>
Improvement map	13	2	6	5	0	7	4	3	4	3	1	0	4	4	0	43	32	8	3	71
Improvement text	0	0	0	0	0	3	3	0	4	1	3	0	0	0	0	18	7	5	6	25
Improvement qCraft	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	1	1	0	3	3
Improvement Minecraft	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	4	4
<b>TOTAL:</b>	<b>250</b>	<b>67</b>	<b>53</b>	<b>75</b>	<b>55</b>	<b>134</b>	<b>47</b>	<b>87</b>	<b>173</b>	<b>47</b>	<b>66</b>	<b>60</b>	<b>67</b>	<b>17</b>	<b>50</b>	<b>206</b>	<b>119</b>	<b>25</b>	<b>62</b>	<b>830</b>

Table 7: The amount of coded fragments respective to their respondent(-family) and their code(-family).