The 5/10 Method: A method for designing educational games

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Abstract

Over the last few years educative games have been on a rise. They have been shown to improve insight, involvement (Marino and Hayes, 2012), engagement in the subject (Wilson et al, 2009) scientific discourse, reasoning and inquiry (Barab et al. 2007). They have been used in schools with success and good results (Ketelhut, 2007). However recent studies show that in spite of this potential games are often misused and are hard to integrate in the instructional environment. Often it is not clear what a game contributes to a students learning or how it should be used because of a lack of learning objectives and outcomes. (Young et al, 2012, Marino et al, 2011). In this thesis I propose a method that provides and clearly states these learning objectives allowing for a better assessment of the contribution it can offer to the existing instructional environment. To do this I combine the widely used design model ADDIE with the instructional design method 10 steps to complex learning by Merriënboer (Merriënboer, 2007). This method is then applied in creating the educational game Moth as a proof-of-concept.

1. Introduction

1.1 Games in Education and Problem Postulation

Since 2007 the game *River City* has been used as a component of a game-enhanced science curriculum to teach science to over 8000 students (Ketelhut, 2007). In this game students are challenged to assist the mayor of a nineteenth-century industrial city in determining why the residents are becoming ill. By investigating evidence and using scientific facts the students have to find out what is going on in the town. The town has grown around a river that flows from the mountains past a waste disposal site and into a bog. The students can interact with the residents of the city, insects and objects, which all can provide evidence to support their scientific inquiry process. Ketelhut found that using games in such a way might be a catalyst for students to increase self-efficacy and increase learning. By combining video games and more traditional curricular materials the accessibility of the content is improved and learning is made more relevant to the students life (Marino and Hayes, 2012).

Games like this engage students in a more direct way, only one of the positive aspects of using games in education. The high level of autonomy in playing games allows students to customize gameplay so it fits better, at least to some level, to their personal and cultural norms (Dieterle, 2009), while still having the benefit of being in a controlled learning environment. It gives the students a way to disassociate from personal perception of their physical appearance or ability levels. This particularly helps students with low self-esteem or self-efficacy (Barab and Dede, 2007). Games will engage all types of players even more if the game allows to personalize aspects of the gaming experience such as developing a unique in-game identity (Wilson et al. 2009).

Kafai et al. (Kafai et al., 2010) show in their studies using the game *Whyville* that the gameplay encourages students' participation in scientific arguments and led to the use of higher-level vocabulary words than they would usually use in normal conversation. Other research shows that scientific games, be they "standard" games, massively multiplayer online (MMO) games or augmented reality (AR) games, support and improve scientific discourse, reasoning and inquiry (Barab et al. 2007; Squire 2010; Klopfer 2008; Steinkuehler and Duncan 2008). More importantly, students from all groups and ages reported that they would prefer to learn science from a game rather than from traditional text, laboratory-based, or internet environments (Marino et al., 2012).

A recent literature review notes that the high degree of variability in current video game designs contributes to inconclusive findings in studies across educational contexts (Young et al., 2012). Even though games can be a very powerful educational tool there is often a problem in integrating them in the instructional environment. Very often the games don't fit well in the curriculum and get misused or neglected. Additionally, it is often very hard to examine whether or not a game contributes to a student's learning because of a lack of clearly defined learning objectives and outcomes (Marino et al., 2011).

In this thesis my goal is to propose a method that provides a guideline to design a game with clearly defined learning goals and objectives, with a place within existing curriculum. The focus is to clearly state the To accomplish this I will discuss the design process in general in section 1.2, and I'll take a look into the Instructional Design System presented by Merriënboer in section 1.3. In chapter 2 I will describe my own method for designing educational games which I will apply in a case study discussed in chapter 3. I will finish with my own conclusions on the method and possible future work in chapter 4.

1.2 The design process

To create an effective method for designing educational games I first take a look into the design process. Many different models to capture or prescribe the design process in a systematic approach have been created over the years (Brooks 2010; Dorst and Dijkhuis 1995; Newel and Simon 1972; Pahl, Beitzz, Feldhusen and de Grote 2007; Ralph 2010). A problem many of these methods share is that they take the design process as a purely intellectual exercise. However, every design involves creativity to at least some degree (Casakin and Kreitler 2005). In computer games this degree is higher than in many other design processes as it consists of multiple media in one design process.

On the other hand, viewing designing as a purely creative exercise is not a solution either. Even though design is a form of art in many aspects, it also has to be useful, functional and valuable, not just original and esthetic (Christiaans 2002). This means that a model describing the design process has to take both artistic and practical aspects of the design process into account. Even though creativity is highly personal and seems a hard to regulate process, a large part of creativity is constituted by cognition and reason (Csikzentmihalyi 1997; Finke, Ward and Smith 1992; Weisberg 1986), this means it is possible to capture the process at least partly in a method to guide designers to better results.

Several approaches to design have been developed over the years. Schön claims in his work that designers alternate between "framing", "making moves" and "evaluating moves" in their process of design (Schön 1983). During the "framing" the designer maintains a 'reflective conversation' with the design to refine it and construct different mental representations of the design situations. These refinements are then carried out and evaluated.

Ralph later describes this process in terms of sense-making, which includes both framing and evaluating moves, implementation or construction of the design object, and co-evolution, which consists of refining the mental representation of the design object in view of its context (Ralph 2010).

Further studies focuses on more specific cognitive components of creative design problem solving. Casakin investigates the effect of metaphors in enhancing creative design solutions (Casakin 2007). Bonnardel and Marmeche, and Casakin compare the difference of use of analogical reasoning between experts and novice designers (Bonnardel and Marmeche 2005; Casakin 2010).

Designing is a form of problem solving. It consists of finding new ways of dealing with a problem, whether they are creative, esthetic or practical ways. During this process new problems will arise, for which in turn a solution needs to be found (Chesbrough 2003). Due to this aspect of designing, the process cannot be linear (Thomke 2003). A good product will always have to be tested, altered and tested again through experimentation. Only when the idea is verified, argued and proven can an idea really become a product (Thomke 2003). Even though this cycle of design and testing seems potentially endless, if it is well integrated it can potentially create shifts in market, industries and even cultures (Chesbrough 2003). This makes it important and necessary to include iteration in the design process.

A widely used method in product design and especially in instructional system development (ISD), such as teaching methods, books and educative games, is the so called ADDIE model. ADDIE is an acronym for

Analysis, Design, Development, Implementation and Evaluation. It incorporates both the steps described by Schön and Ralph and the iteration aspect.

The exact interpretation of this method varies but it always consists of these five global steps (see figure 1). Beyond that there is a widely shared understanding that when used in ISD models these processes are considered to be sequential but also iterative (Molenda 2003). After evaluation, changes will be made according to the result of the evaluation to improve the product leading eventually back to evaluation and so on until the desired result is reached.

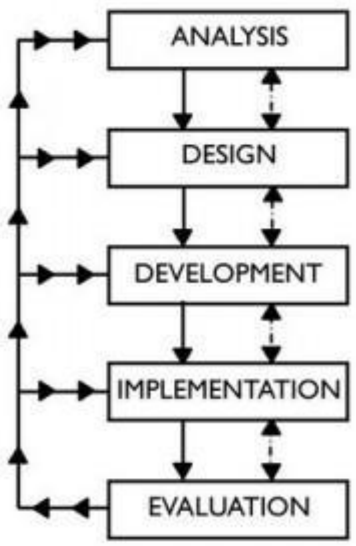


Figure 1: ADDIE based ISD model (Grafinger, 1988)

The origin of this method is unclear. Branson is the first to show a similar method (Branson 1978) in a research for US military teaching methods. Since then it has appeared under different names and descriptions but with the same basic method (Molenda 2003; Wang and Hsu 2005).

The ADDIE model provides a good basic skeleton to create an educational method (Grafinger 1988). I will use it as a global framework in my method, providing a global framework for the more specific method of design using the Ten Steps to Complex Learning (Merriënboer and Kirschner 2007) described in the next section.

1.3 Ten Steps to Complex Learning

In combination with the ADDIE model I use the method described by Merriënboer and Kirschner (2007) in their book on creating educative methods with a focus on complex tasks "Ten Steps to Complex Learning". In this part I will cover the basics of their method and how it is applied. In their method they describe a more holistic approach to designing a learning method as opposed to an atomistic design approach. A holistic design approach, in contrast to an atomistic approach, does not analyze a complex domain into unrelated pieces, but simplifies complex tasks in such a way that learners might be confronted with whole, meaningful tasks right from the start. The 10 steps are based on Merriënboer's earlier work, the 4C/ID method (Merriënboer et al., 1992).

1.3.1 4C/ID Method

The 4C/ID approach has the basic assumption that the blueprints for complex learning can always be described by four basic components, namely: learning tasks, supportive information, procedural information and part-task practice.

Learning tasks can be taken as a very broad term. They may refer to a case that has to be studied, a project that has to be done, a problem that needs to be solved and so on.
Supportive information is all information necessary to perform non-routine tasks such as problem solving and reasoning. Procedural information is all information necessary to perform parts of the task that are always done the same way. Finally part-task practice is needed if the participants need to get a very high level of automaticity in their task. Each of these blueprint components will be discussed in more detail in chapter 1.3.2

Each of these blueprint components are developed and designed using the 10 steps. Of these 10 steps, 4 are "design" steps (design learning tasks, design supportive information, design procedural information and design part-task practice). The rest is auxiliary to these steps and is only performed when necessary.

These 10 steps are:
1. Design learning tasks
2. Sequence task classes
3. Set performance objectives
4. Design supportive information
5. Analyze cognitive strategies
6. Analyze mental models
7. Design procedural information
8. Analyze cognitive rules
9. Analyze prerequisite knowledge
10. Design part-task practice

Pebble in the pond technique
The 10 step method follows a so-called pebble-in-the-pond model (Merril, 2002). In this model the learning tasks represent a pebble thrown in a pond. Each of the subsequent steps grows from that first step like ripples in the water, adding more and more until a full method emerges.

1.3.2 The 10 steps in detail

Learning tasks
The first three steps have the goal of developing a series of learning tasks that serve as the backbone for the rest of the method.

1. Design learning tasks
2. Sequence task classes
3. Set performance objectives

Step one aims to determine the overarching learning task or tasks that best represent the whole of the skills and knowledge the learner has to posses. These tasks are called the epitome, the most fundamental tasks that represent the skill (Reigeluth, 1987; Reigeluth and Rodgers, 1980). This ensures that right from the beginning it is very clear what the final goal of the training program is.

In most cases there will be more than one learning task. The second step is to specify an ordering of these tasks with increasing difficulty. The goal is to make a smooth transition from begin to end of the training with the easier tasks at entry level and harder tasks in the end.
To give the participants feedback on their progress as well to decide when to advance from one class to the next, standards need to be defined that have to be met for acceptable performance. To do this the next step consists in specifying performance objectives that articulate the standards that learners must reach to carry out the tasks in an acceptable fashion.

By taking this pebble-in-the-pond approach all goals, objectives and how they are met are defined right at the start, giving a stable basis for applying the rest of the method. It also makes having to adjust or abandon objectives that are stated early in the design process less likely as the the design process evolves..
To illustrate the first three steps I will use the example of learning to design a building. The learning tasks in this example could then be to follow a list of given requirements, build it according to safety laws of the country, know how to calculate physical properties such as forces working on the support etc.

Sequencing these tasks is based on complexity of the tasks and the effort and insight needed to perform them. Such a sequence could look as follows.

1. Build according to safety laws
2. Calculate physical properties
3. Follow the list of given requirements

I made this sequence bearing in mind that safety laws remain constant, while requirements from clients change from project to project or even change during projects and might even be at odds with laws of the country or even the laws of physics.

An example of performance objectives would be a description of how well the building should resists time, the elements and natural disaster, it should fulfill all building laws and a measure of how happy the users of the building should be living or working in the building.

Component knowledge, skills and attributes

The next steps identify the knowledge, skills and attitudes needed to perform the learning tasks. These will then be connected to the basic skeleton of learning tasks developed in step 1 to 3. Merriënboer makes a distinction between supportive information, procedural information and part-task practice.

Supportive information is information necessary to perform the non-recurrent aspects of the learning tasks. These are related to problem solving and reasoning. The more complex a task gets, the more supportive information is needed to perform it.

For developing the supportive information the following steps are taken.

4. Design Supportive Information
5. Analyze Cognitive Strategies
6. Analyze Mental Models

Often supportive information is already available and only needs to be adjusted for the specific needs of your educational design, in this case steps 5 and 6 can be skipped. Experts in the field often have clear ways of solving problems and can provide this supportive information. In many cases educational institutes have established methods that describe in detail how to solve particular problems. In those cases the supportive information is available and can be used directly. If the supportive information has to be designed from scratch steps 5 or 6 have to be taken.
Cognitive strategies cover ways to look at a problem, where to start and how to finally solve a problem in a specific task domain. It is analyzed as a systematic approach to problem solving (SAP), containing a description of phases in problem solving and rules-of-thumb that may help to complete each of the phases.
Mental models are a representation of how the task domain is organized. It is analyzed by looking at conceptual models (what is this?), structural models (how is this built?) or causal models (how does this work?).

In the example of designing buildings supportive information would be how to approach clashes between clients' wishes and laws of physics, for example when the client wants a big unsupported overhang. The supportive information would then be how to either adjust the design in such a way that the overhang can safely be built, or to convince the client to review their demands. This is an example of a cognitive strategy as it gives a strategy on how to solve the problem that is not the same in all cases and cannot be solved by simply following an algorithm. A mental model in this field would be how the building sector is organized and what the pipeline from design to final result looks like.

Parallel to the design of supportive information is the design of procedural information. Procedural information is information necessary for performing recurring aspects of a learning task. It describes how to perform these aspects. The best way to present this information is exactly when the participants are working on the learning task. Procedural information quickly fades away, often replaced by new specific information for carrying out new procedures (Merriënboer and Kirschner, 2007).

The steps for developing procedural information are:

7. Design Procedural Information
8. Analyze Cognitive Rules
9. Analyze Prerequisite Knowledge

If useful instructional material is available, such as quick reference guides or job aids, steps 8 and 9 can be skipped. In that case step 7 consists in updating that information and linking it to the appropriate skills. If procedural information has to be designed from scratch steps 8 and 9 are of help.
Cognitive rules are a mental representation of a consistent relationship between particular conditions and a (mental) action that has to be taken under these conditions. They can be represented as if-then rules or a combination of if-then rules.
Prerequisite knowledge is basic knowledge that is needed for the use of cognitive rules. This consists of concepts, principles and plans.

In the example of teaching building design procedural information is for example how to calculate the force put on the support, and the amount of force a material can support. Calculating the force is an example of a cognitive rule while the amount of force a material can take is prerequisite knowledge.

10. Design Part-task Practice

In some cases a tenth step is necessary to develop a high level of automaticity. This is often the case in practicing possibly dangerous situations. In this case it is better to practice the automaticity in smaller tasks that are less dangerous or expensive when things go wrong. Information gathered in step 8 will be useful when in designing these part-tasks.

When designing a building it is obviously too expensive to build a complete building to practice the design. Part task in this case can vary from calculating the force on existing buildings to designing a building in a simulation environment or scale model.

While looking at a structured method like this it is easy to forget that iteration will always occur in a real life design process. It is possible and even encouraged to go back to previous steps to adjust them to needs that arise in later steps.

2. A method for educational game design

2.1 The goal of the 5/10 method

The goal of my method is to have a standard model for designing educational games. It should guide the designer to state clear learning goals and take the existing teaching methods into account. Following this method the designer should acquire the necessary background knowledge to develop a game that helps students reach all designed learning tasks. In this chapter I will combine the 5 steps of the ADDIE model with Merriënboers 10 steps to complex learning in a way aimed specifically at educational game design, giving the method the name "5/10 method".
Combining these two methods in the way described in this chapter will help to design a game that has clear learning goals and a way to complete them. This will allow the designer to show to what degree the game will help students understand the subject matter. This way the teacher is to assess the game's value in teaching. Furthermore it guides the designer to work with existing teaching methods and experts allowing for a better integration in the existing curriculum.

The method focuses on the instructional system design and largely ignores the artistic side of game design such as visual, audio and specific level design. While these are definitely important for game design, they are a separate field of research and out of scope for this thesis.

The most essential phase of the ADDIE model is the Design phase where all choices are made for the final product. This is where the 10 steps will be used to ensure the game will be designed with clear learning goals in mind and providing the player with the right information at the right time.

In chapter 3 I present a case study using this method to create an educational game for studying high school level optics.

2.2 The 5/10 Method

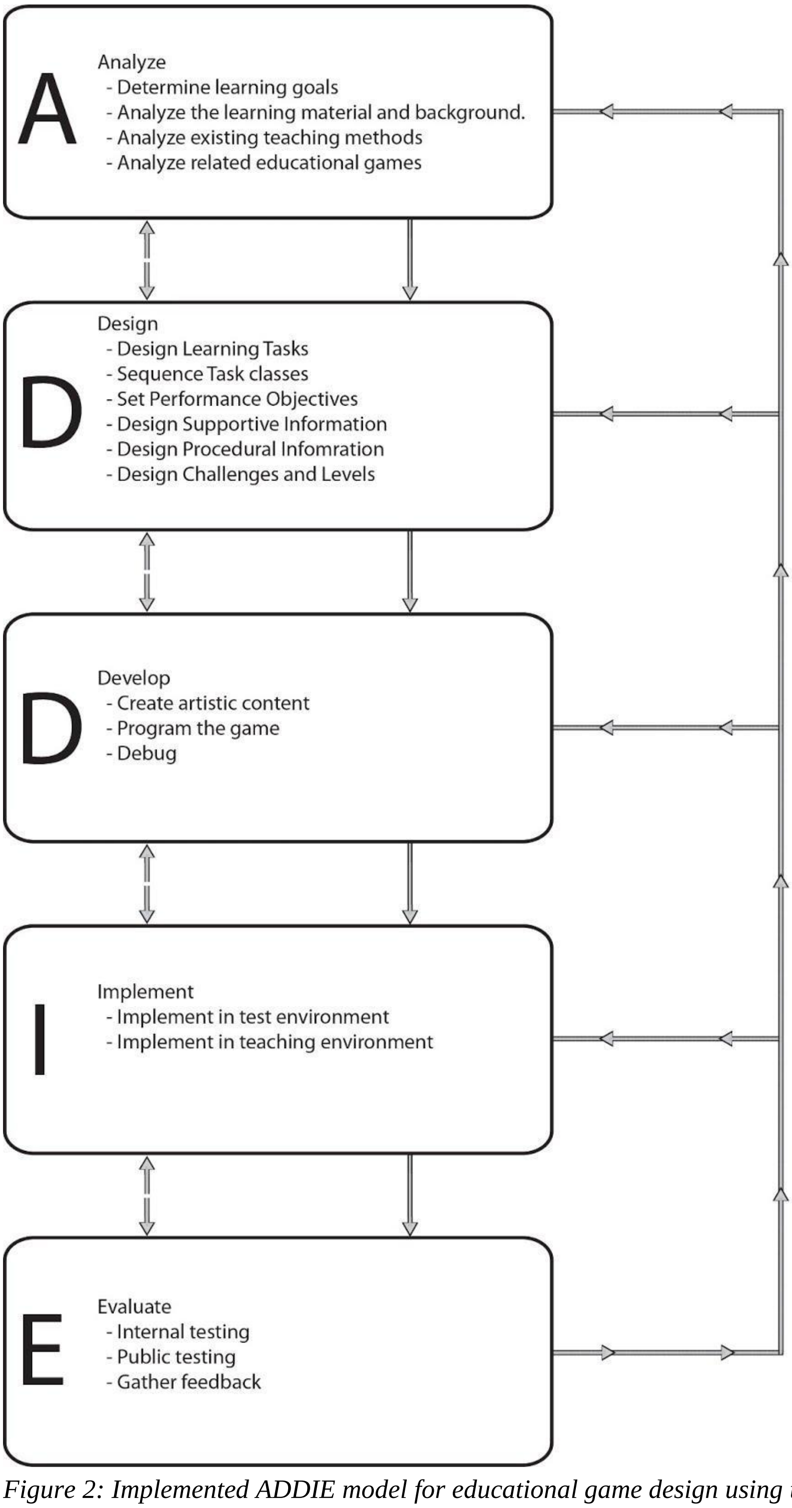


Figure 2: Implemented ADDIE model for educational game design using the 10 step method

2.2.1 Analyze

The first step of the ADDIE model is analyze. This step consists of four smaller parts that together will answer the basic questions of what the game will be about, what has been done before, what the details are the game will have to teach, and how this is traditionally taught. Each of these steps will then be discussed in detail.

- Determine learning goals
- Analyze the learning material and background.
- Analyze existing teaching methods
- Analyze related educational games

Determine learning goals
The most important part of the design is determining the goal of the finished product. What should the designed game accomplish? Because a design process starts with an idea, the global learning goal often is already known. This can be teaching a fireman officer to make decisions or helping a high school student study for an exam in physics. It is not necessary to determine all subgoals at this point, as these will be worked out later in the Analyze and Design phase.

Analyze learning material and background
Analyze the subject. Work out in detail what the subject is about and what parts it consists of. This research will help define the subgoals. Refine the global goals set in the previous step and clearly state what is going to be covered in the game. Doing this provides those involved in the design process with clear goals and by showing exactly what is covered in the game teachers in the field can easily see what role it can fulfil in their curriculum.

Analyze existing teaching methods
Do research on existing teaching methods. At this point it is very beneficial to work together with an expert in the field. Preferably a teacher or instructor. These experts can provide more information about how the game fits in the existing curriculum, provide more insight in the subject matter and on how it is usually presented to students. Decide what place this game will take in the existing teaching method, whether if it will replace the teaching method in place or be used in conjunction with existing methods.

Analyze related educational games
Find and evaluate existing games that cover the learning goals determined in the previous step. List the positive and negative aspects of each of those games. At this point it is important to determine if a new game in this field is needed.

2.2.2 Design

The design phase is at the heart of the ADDIE method. All important decisions about the game design are taken in this phase. The 10 steps to complex learning proposed by Merriënboer et al. can be adjusted and used to describe all the steps necessary in the design process for meeting the learning goals and how to integrate these goals in a game environment. Each step will be accompanied by a small example to illustrate the basic idea. For a more complete and thorough example read the case study in chapter 3. The ten steps presented here are the ten steps described in part 1.1.3 adjusted for educational game design. During the process of following the ten steps, be sure to keep a document for reference during the development step. It should describe all choices made and information designed in each step.

Step 1: Design learning tasks
Find the global tasks that represent the skills

The first step stays the same. The goal is to state the learning tasks that should be performed or practiced using the game. Describe the most overarching learning tasks and describe the material to be learned in as few tasks as possible, while still clearly delineating the material to be learned in the game. This step refines the goals found in the Analyze phase. The goal of describing this in as few tasks as possible is to clearly define the area covered in the game without going into detail.

For example when designing a game to teach music theory learning tasks could be to hear intervals, read notes, read in all keys, to understand and use the musical vocabulary in the right circumstances and to know the global history of music. Information such as the specific rules of reading notes, rules of harmony, the vocabulary itself and the structure of the history is covered in step 4 to 9.

For subjects with standardized exams such as high school subjects or traffic theory for a drivers licence the learning tasks are often very clearly defined and publicly available.

Step 2: Sequence task classes
Order the tasks in order of difficulty and determine all the skills, knowledge and attitudes necessary to master the complete task.

Sequence the tasks defined in step 1 in order of difficulty. In many cases this ordering will be subject to personal judgement as different people have difficulty with different subjects. The sequence can differ between different target audiences. Working with an expert in the field, especially a teacher or instructor will help determining a good order as they know from experience where most problems occur in the teaching process. Often the order the subjects are presented in existing teaching methods are a good indication of the complexity of the tasks.

In the example of musical theory a possible sequence is

1. Read notes (basic)
2. Read notes in different keys
3. Know and use musical vocabulary
4. Know global musical history
5. Hear intervals

While this might be a good sequence for a lot of people, hearing intervals is a very easy task for people with perfect pitch. As this phenomenon is much more common among Asians, when designing the same game for a mostly Asian audience the learning task “Hear intervals” may be higher up the list.

The second part of this step consists of gathering all skills, knowledge and attitudes necessary to master the complete task. This information should be gathered in the Analyze phase. The goal in this step is to order it and connect it to each of the learning tasks.

In the musical example:

Read notes (G clef)
- second bar is the note G
- notes go from A to G then go back to A
- # increases tone by half a note and is called “sharp”
- b decreases the tone by half a note and is called “flat”
- etc.

Step 3: Set performance objectives
Specify performance objectives that articulate the standards that learners should reach to carry out the tasks in an acceptable fashion. Design the reward system for the game.

Clearly define the performance objectives that have to be met for each of the learning tasks. This can then be used to define a reward system for the game. The goal of this reward system is to motivate the player to keep playing the game, and keep completing the challenges based on the learning tasks described in part 1. This reward system can take on any form that motivates the player to play and finish the game, completing all challenges and learning to do all the learning tasks. It can be as simple as earning points for each correctly answered question or simply advancing to the next level or as complicated as advancing through a skill tree with an achievement system.

In the musical theory example.

1. Name all notes in any given key when presented in a random order.
2. Same as 1 but in all clefs
3. Provide the definition for all musical terms
4. Name all musical eras and their major composers
5. Name the interval between any 2 or 3 given tones

Reward system: Earn points for giving the right answer and extra points for answering fast. Points given for each subject are as follows
For points 1 to 4 the answers are either right or wrong. In that case it is possible to give points for the percentage of rightly answered questions.

% correctly answered questions	rating	points
80	adequate	100
90	good	300
100	perfect	500

For the task of hearing intervals however can be partly right or almost right. For example the interval itself can be right, but not the place on the scale, or the listener hears the right harmonic, but interprets it wrong. In this case points per answer will be given depending on how right the player is.

Answer	rating	points
Interval right	good	50
Harmonics right	adequate	20
Both right	perfect	100

Step 4: Design supportive information
Design the non-recurrent information and design the way it is presented in game. The supportive educational design can be updated from existing material. If no material exists do step 5 and 6.

Supportive information for educational design consists of two parts; the educational and the gaming supportive information. I will go into detail for both of them here, starting with educational supportive information.
Gather and describe all educational supportive information, the information related to problem solving and reasoning. This consists of all non-recurrent information such as historical dates, context specific information and rules-of-thumb, as described in chapter 1.3.2.

In the musical theory example this information includes the name of the note line on each music bar, exact dates in musical history, the function of # and *b*, names of intervals, the fact that the interval between B and C, and E and F is only half a tone while for the rest the distance is one etc.

When integrating supportive information in a game, this information can for example be supplied as pop-up reminders when the player answers a question wrong, increasing the detail and amount of information given each time a wrong answer is given.

Supportive information on the game itself consists of how to play the game and reach the final goal. To design the supportive information on the game itself do the following:

- Decide on the goal of the game (how to finish the game, the motivation of the player etc.)
- Decide on a genre of the game (Real Time Strategy, Role Playing Game, Puzzle, First Player Shooter etc.)
- Describe the general structure of how to solve the challenges in the game (in a puzzle game, how should the player approach the puzzles, in an RTS this can contain strategies)

While the genre of the game is not technically supportive information itself, it does prescribe the supportive information about the way the game has to be played and the global goals, which should be designed here.

Note that this information does not always have to be explained explicitly in game. This might not even be desirable as it may spoil the challenge in the game. However it is very important to have this information when designing the game.
Also note that game design, like any product design is a fluid process with a lot of iterations (Trip and Bichelmeijer, 1990). This means that information decided on here might be subject to change during the coming steps and even phases of this method.

This information is classically provided implicitly by gameplay or more explicitly in tutorials.

In our music theory example the genre could be a Puzzle game where the player has to find their way through a haunted castle solving puzzles and tasks about music theory to keep the ghosts at a distance and make it out alive.
Defining the genre as a puzzle game gives a clear frame of mind for designing the challenges later in the design process. The puzzles could entail anything from putting dates in the right order to combining notes into harmonious combinations. While doing these puzzles the ghosts are slowly closing in on the player, going even faster when the player gives an incorrect answer but falling back for each correct answer. The goal is to escape the house without getting caught by the ghosts.

Step 5: Analyze cognitive strategies
Find systematic approaches for problem solving.

This step is only needed if no teaching method exists on the subject. It analyzes strategies to solve problems such as describing the phases of problem solving and rules-of-thumb that help complete each of these phases. An example in musical theory is how to use harmonics to invoke the right emotion with people.

Step 6: Analyze mental models
Analyze conceptual models, structural models and/or causal models to design supportive information.

This step is only needed if no teaching method exists on the subject. It analyzes conceptual models, or descriptive information such as facts, dates and definitions, structural models describing structure such as how a composition is structured and what constitutes a harmonious chord and causal models that describe the working such as the mechanics of a piano, explaining how it's built and why it works..

Step 7: Design procedural information
Design the recurrent information and design the way it is presented in the game. This can be updated from existing material. If no material exists do step 8 and 9.

Gather and describe all procedural information needed for the game. This information describes exactly how to perform the recurrent actions needed for the learning tasks. In the 5/10 method this consists of two parts; the procedural educational information and procedural gaming information.

Educational procedural information includes any step by step procedures that are done the same way every time. This information is often already available in the form of reference guides, manuals or job aids.

In the musical theory example:

How to read a note?
1. Start at the known bar (g for g clef, f for f clef etc.)
2. Count up or down towards the note using the scale (a-g then back to a)

3 Include sharp or flat if in the key
4 Apply any sharps or flat added locally
5 Name the note

The gaming procedural information consists of the interaction of the player with the game. How to control the game and the interaction with the interface. Even more than the supportive gaming information the procedural gaming information will grow and change during the design process. This information should answer the following questions:

- How does the player control the game? (This includes navigation, interaction with the environment etc.)
- What variables play a role in the game (such as score, health points, quests etc.)
- How does the game interact with the player (effects of monsters, power ups etc.)

The procedural gaming information in the musical theory example should include how to interact with the puzzles, and how to move from one puzzle to the next. It should include what will happen if the ghosts catch the player, description of score, time and lives and how progress in the game is shown.

Both procedural educational information and procedural gaming information should be presented at the moment it is needed. Procedural information quickly fades away, often to be replaced by new specific information for carrying out new procedures. Procedural gaming information will mostly be presented in the form of tutorial levels, explaining how to play the game while playing it, providing the information when it is needed. The same goes for procedural educational information, introducing cognitive rules and prerequisite knowledge the first time a player encounters a problem for which it is needed.

Step 8: Analyze cognitive rules

Analyze the mental representations of consistent relationships between particular conditions and (mental) actions that have to be taken in these circumstances.

This step is only necessary if no teaching method exists on the subject. Analyze the possible circumstances and what to do in these situations. These rules can be represented as if-then rules. In the example given in step 6 it is the structure of how to solve the problem of reading a note. An example in the music theory would be if a # precedes a note the note has to be played half a note higher. In gaming it can be if the player hits an enemy, the player will lose a life point.

In some more complex cases these rules grow into big algorithms with complex if-then paths, describing decision trees that include many exceptions and special cases. In this case it is important to present the most basic situation first, adding more and more rules of exception and special cases in the course of the game. This way the player will have a solid understanding of the basics of the decision tree when learning the exceptions to the rules.

Step 9: Analyze prerequisite knowledge

Analyze the concepts, principles and plans needed to use the cognitive rules.

This step is only necessary if no teaching method exists on the subject. Analyze the knowledge needed to perform the rules found in step 8. In games this can include information like “enemies need to be killed” or the categories of obstacles that can be encountered in game. Note that there is a difference between the prerequisite knowledge that enemies need to be killed and the specific enemies in the game. While the exact enemies and obstacles and enemies are designed in the last step of the design phase and worked out further in the develop phase, in this step the information that enemies have to die as opposed to for example run from is designed. In the example from step 7 the prerequisite rules is the information needed to apply the rules described in step 8.

- Music notes go from a to g then again a

- The bar where the symbol of the clef begins is known by the name (g starts on the g-bar)
- # is called sharp *b* is called flat
- etc.

Step 10: Design challenges and levels
Design levels and sublevels dividing the learning tasks into playable levels with sub-goals.

This step differs from the original 10 step method by Merriënboer. In a digital game environment tasks are very rarely dangerous or extra costly since a game is inherently a simulation environment. This means that designing part-task practices for the sake of safety or money is not needed. Instead in this step is designed the challenges and levels for the game.
To do this, divide the tasks that are defined in step 1 to 3 into challenges the player will encounter, which combined with the supportive and procedural information, from step 4 to 9, form the basis for level design.

Use the information from step 2 to order these levels. The sequence created in step 2 can be the exact sequence the subjects come to pass in the game, but a more effective way presented in Merriënboer’s work is to make use of cycles (Merriënboer et al., 2007). Start with a sequence of problems in the order described in step 2, using simple problems with much help in the form of supportive information and tutorials (procedural information). Then go to the next cycle providing more complex problems and less supportive information, until the performance objectives set in step 3 are met.
The sequence created in step 2 should be a guideline and can be varied upon when designing the levels if it fits the game design better.

If needed, go back at this point to step 4 and 7 to add to or change the supportive and procedural information if needed and design the interface. At this point the skeleton of the game is complete. The interface is complete as well as the goal of the game including a reward system (step 1, 3 and 4). The flow of the information and teaching material throughout the game has been determined (step 2, 4 and 10) and the challenges met on the way have been designed (step 10).
All details such as visual, audio and exact level design should be based on the target audience and personal style of the game developer.

2.2.3 Develop

The Development phase consists of using all information and design choices made in the previous phase to create an actual product. As in any part of the design process, development happens in small iterations, debugging and improving. During the development it is likely that problems in the original design show up, which may lead to adjustments. Make sure that after applying these adjustments the learning tasks have not changed and all necessary information is still given at the right time.

2.2.4 Implement

Deploy the game in the test environment. In the first few cycles this will most likely be an internal test environment. Make sure the game works and is largely bug-free outside the development environment. Once the game is tested internally for bugs it should be implemented for use by the target audience. In case of educational games this means it will be made available to students learning, or wanting to learn, the learning goals set when starting the game design. Make sure the game is also tested by teachers and/or experts in the field. These people can give advice about how to fit the game in the existing curriculum and may notice (sub) learning tasks that are missing or not well represented.

2.2.5 Evaluate

After implementing the game in the test environment gather feedback. Interview the users on the important aspects of the game. In the evaluation keep in mind the following aspects. Note that not all of these aspects have been mentioned before but have been left deliberately out because they apply to artistic design and the entertainment value of the game. While these aspects are out of scope to cover in the 5/10 method they are still important for good game design in general and should not be neglected in the evaluate phase.

Each of these aspects has a short description in brackets what part of the design process they apply to. This helps to decide where changes have to be made in case of negative feedback on the subject.

Gameplay:

- Enjoyable (Artistic design)
- Motivating (Artistic design)
- Learning Curve (Task sequence, step 2)
- Quality and usability of the interface (Artistic design and procedural information, step 7)

Artistic value:

- Style of graphics (Artistic design)
- Music and sound choices (Artistic design)
- Does the art contribute to or hinder the learning experience (Artistic design)

Educational value:

- Are the learning goals met (Learning tasks, performance objectives, step 1, 3 and 10)
- Does the game motivate students to work on the subject
- Does the game increase understanding and insight on the subject matter (Procedural and supportive information, step 4-9)
- Does the game fit in the existing curriculum.

Evaluate the feedback and use the information to make adjustments to the design, doing new research if needed. Implement these changes in the game and redeploy the game. Test again and gain feedback. Keep repeating the cycle until a satisfactory final result is reached.

Even though the method is presented linearly it is important to keep in mind that in practice the whole process consists of many small iterations going back and forth between phases in the ADDIE model when needed. For example during the Design phase, more analysis and research might have to get the information you need for the design. During the development the design might have to be adjusted and during the deployment the program might have to be changed to run on different systems etc. So follow the steps of the method, but don't be afraid to go back to a previous step when needed.

3. Case Study: Moth

In this chapter I will illustrate the use of the method in a case study of a game I designed myself according to the method described in chapter 2. In this case study I will go through the whole process from Analyze to Evaluate in the first cycle of game design. I will finish by evaluating the feedback and describing what needs to be done in the next cycle of the design method. For clarity the case is described in a strictly linear way. In practice however there is a tendency to go back and forth between phases at times to adjust to new found problems or insight, as described in chapter 2. The final result can be downloaded on this website:

https://sites.google.com/site/yarentertainment/

3.1 The goal

The goal of this game is to function as a practice tool for optics in the final year of the VWO (Preparatory Scientific Education) level of high school in the Netherlands. The game is to be used to practice for the final exam, providing a new medium for and a fresh look at the material while maintaining the level of difficulty consistent with the final exam.

3.2 Using the Method

3.2.1 Analyze

The first step consists of the four sub steps described in the method in chapter 2.

- Determine global learning goals
- Analyze the learning material and background
- Analyze existing teaching methods
- Analyze related educational games

Determine global learning goals
Optics is a mandatory part of the high school physics curriculum. As such there is a national standard that has to be met to pass that part of the physics state exam. These goals are available online and used by all high schools of the VWO level for students taking physics.

For this game I use the learning goals presented in part E2 of the VWO physics exam requirements 2012 of the Dutch educational system (Ministry of Education, Culture and Science, 2012). These are the following:

1 Know and use Refractive Index and Snellius Law
2 Know and use the Law of Reflection
3 Know and use the lens formula, including being able to calculate and use focus points, lens strength and use construction rays for a positive lens.
4 Calculate with magnification using the magnification formula
5 Know that different wavelengths of light (and as a result different colors) have different refraction indices.

Analyze learning material and background
According to the Exam Requirements the student needs to know and use all defined optic formulae (see figure 3).

$$\frac{\sin i}{\sin r} = n,\ \sin g = \frac{1}{n},\quad S = \frac{1}{f},\ \ \frac{1}{f} = \frac{1}{b} + \frac{1}{v},\ \ N = \left|\frac{b}{v}\right| = \frac{\text{Image Size}}{\text{Object Size}},\ f = \frac{c}{\lambda},$$

$$\sin\alpha = \frac{n\lambda}{d}\ \ (n = 1, 2, \ldots).$$

Figure 3: Formulae for Dutch high school optics (Ministry of Education, Culture and Science, 2012)

I will give a short explanation and description of use for each of these formulae. This information is based on the physics teaching method "Newton". (Kortland, 2010).

Rules and Formulas:

- **Global:** The normal is the line perpendicular to the surface at the given point. On a circle (or curved line part of a circle) the normal is the line going through the center of the circle.
- **Reflection:** angle of incidence is equal to the angle of reflection

  $$\angle i = \angle t$$

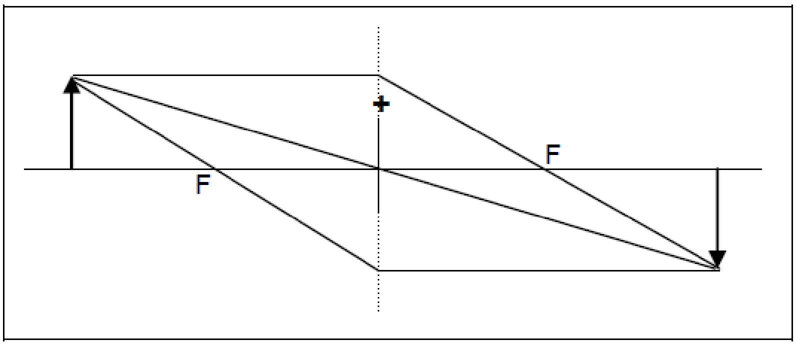
- **Magnification:** Magnification is image size divided by the object size as well as the absolute of image distance divided by object distance.

$$N = \left|\frac{b}{v}\right| = \frac{\text{Image Size}}{\text{Object Size}}$$

- **Lens formula:** focus point is the point on the axis of a lens or mirror to which parallel rays of light converge or from which they appear to diverge after refraction or reflection
- **Lens Formula:** focal point (f), image distance (b) or object distance (v) can be calculated using the lens Formula:

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{b}$$

- **lens formula:** construction lines are made by drawing lines using the following rules:
  - a light ray going through the optical center of the lens continues unchanged through the lens
  - a light ray going through the focal point **before** entering the lens continues parallel to the lens axis after the lens
  - a light ray parallel to the lens axis before entering the lens will go through the focal point behind the lens



- **Refraction:** Refraction is the bending of light when it moves to a different medium with a different optical density. The degree to which this happens depends on the refraction index of the medium.
- **Refraction:** Angle of refraction (r), angle of incidence (i) or refractive index (n) can be calculated using the following formula:

$$\frac{\sin i}{\sin r} = n$$

- **Refraction:** Refraction index from for light going from the material to air is the inverse of the refraction index of light going from air to material as shown by the formula:

$$n_{B \to A} = \frac{1}{n_{A \to B}}$$

- **Refraction:** Critical Angle is the smallest angle of incidence at which a light ray passing from one medium to another less refractive medium can be totally reflected from the boundary between the two.
- **Refraction:** Critical Angle (g) can be calculated, given refractive index (n) using the following formula

$$\sin g = \frac{1}{n}$$

- **Refraction:** Refractive index for light with longer wavelengths (red) have smaller refractive indices than those with smaller wavelengths

While working with formulae and calculating light paths constitutes a large portion of the exam material, about 25% to 30% consists of so-called insight questions. These questions are in the form of real life situations that have to be explained with insight in the workings of physics, and the idea behind the formulae. While these questions are very important to assess the insight the student has on the subject, they are difficult to implement in a game. The idea behind them is to describe reasoning. Creating the gameplay to deal with this kind of exercises is rather complicated. For this reason I decide to focus on practicing the formulae and factual knowledge.

To summarize, the game will cover formulae, calculating and practicing when to use what to find the answer, but it will not cover insight questions.

Analyze existing teaching methods

As mentioned in the last part I use the Meulenhof teaching method “Newton” by Kortland (Kortland, 2010) as a target teaching method for use with my game. This method is widely used in the Netherlands and prepares many students each year for the state exam.

I also studied state exams of the last 3 years, specifically looking at optic problems. Many questions in exams consist in combining multiple disciplines of physics into a single real-life example. However, because of limited time and money resources and the fact that this game is a proof-of-concept I decided to keep my focus and stick with the learning goals selected in the first section of this phase.

I collected exercises and questions from both the Newton method and state exams of previous years to base my level design on in later stages and give me insight in the way the material is practiced in traditional teaching methods..

To further increase my understanding of the subject as well as discuss the possible use of games in conjunction with the Newton method I interviewed high school physics teacher G. van Hunnik. In this interview it was very clear that the possibility of an enhancement of the teaching method in the form of an educational game would be a very welcome change or both the teacher and students.

He explained how students traditionally prepare for the exam. Students practice all year around with the different aspects of physics they were taught over the years, recapping and doing practice exams and old state exams to practice the material and get familiar with the style of the exams.

He also confirmed that while there are educational games available, the quality varies widely and they do not fit in the curriculum being either too easy or too advanced for high school students as described in section 1.1. Van Hunnik also pointed out that a game as an extra, optional tool might be very beneficial to most students and will be adopted, especially amongst students already playing games for entertainment. However it probably will not be adopted as easily by students with no tendency towards gaming, or students who attach social stigmas to gaming which, in spite of becoming less over the last years, is still an issue.

Van Hunnik also mentioned that while he is a proponent for games and other electronic aids to support teaching he wouldn’t want it as a replacement of current methods because the change would be too great and it would be too hard to guarantee the quality of education.

He also offered to help by allowing the use of this game in school once ready for testing, thus supplying me with a test group that is exactly my target audience.

With the information gathered in this step I confirmed my decision to use the game as an aid in preparation for the state exam, but not as a teaching method on its own. It should be used as a variation on traditional preparation for the state exam.

Analyze related educational games

There is no shortage of existing educational games in the field of physics. Most of them focus on the more visually explicit aspects of physics like mechanics and gravity. But even the less popular physic subjects such as optics are well represented (see Figure 4).

Figure 4 Existing optics educational games

However the target audience of these games seems to be almost universally children younger than 14 years old. The focus in these games often is limited to playing around with mirrors and explaining the very basics of optics. While very useful and even entertaining these games do not fit in the high school curriculum and certainly do not prepare for the state exam.

The other kind of "games" I found were simulations. Again mostly based around mechanics these games have a heavy emphasis on simulating situations. These simulations can be very useful in the classroom environment as an alternative to real-life setups, and allow students to play around themselves to get more insight in the subject. This, however useful, fills a completely different need from the need I want to fulfill.

These findings, together with the confirmation from the interview with Mr. van Hunnik lead me to the conclusion that a game targeting end high school VWO level optics is both unavailable at the moment and desired, justifying designing one.

3.2.2 Design

The Analysis phase gives a solid base to start the Design of the game, as it supplies me with the information i need. I know the goal of the game, the material and its background, the justification for making the game and how it fits in the curriculum. I will now follow the 10 steps as described in the 5/10 method in chapter 2.

Step 1: Design Learning Tasks

Find the global tasks that represent the skills

The learning tasks are discussed in the Analyze step and are based on the exam requirements for VWO state exam candidates as established by the Dutch Ministry of Education, Culture and Science (Ministry of Education, Culture and Science, 2012).

Exam requirements:

1. Know and use Refractive Index and Snellius Law
2. Know and use the Law of Reflection

3. Know and use the lens formula, including being able to calculate and use focus points, lens strength and use construction rays for a positive lens.
4. Calculate with magnification using the magnification formula
5. Know that different wavelengths of light (and as a result different colors) have different refraction indices.

These exam requirements can be formulated as learning tasks as follows:

- Correctly calculate the refractive index, angle of incidence or angle of refraction using Snellius Law
- Correctly Calculate angle of incidence or reflection using the Law of Reflection
- Correctly use construction rays and focus points in problems involving positive lenses
- Correctly calculate magnification, image distance, object distance, image size or object size using the Law of Magnification
- Correctly use the right refractive index based on the color of the light.

Step 2: Sequence Task Classes
Sequence the tasks in order of difficulty and find all skills, knowledge and attitudes necessary to master the complete task

It is difficult to objectively order tasks based on difficulty. Different people have difficulties in different areas of the subject. The sequence presented here is based on complexity of the learning tasks and created in association with physics teacher Mr. van Hunnik and does correspond to the order the subjects are introduced in the teaching method Newton. This sequence however might not correspond to every students view on difficulty depending on personal preference and strengths in the field of optics.

Learning tasks in order of complexity:

1 Law of Reflection
2 Formula of Magnification
3 Lens formula/focus
4 Snellius Law and refraction, including different wavelengths

In game I will use this sequence to order levels in cycles using the following global structure. The game will start with easy levels, letting the player get used to the controls and introducing the player to the more simple concepts. In the next levels all skills will be covered in the challenges. These challenges will be based on existing exercises from traditional teaching methods. The last levels will combine all the skills learned into harder challenges.

The knowledge needed to perform these learning tasks is discussed in the previous phase, and will not be discussed here again to prevent redundancy. See Appendix A for a complete overview of the learning tasks including a complete overview of the knowledge needed for performing them.

Step 3: Set performance objectives
Specify performance objectives that articulate the standards that learners should reach to carry out the tasks in an acceptable fashion. Design the reward system for the game.

Software that interprets calculations is very hard to program. For this reason I decided to only allow a correct answer. There is no partially right answer and the calculation itself is not taken into account.
The goal of this game is to finish it. It has no point or grading system. While a grading system might be useful if the game is used as a replacement for the traditional curriculum, it is of no extra value to the role the game will play, namely practicing for the state exam.

For each of the learning tasks there should be a specification of when the task is performed in an acceptable fashion. As mentioned before, only correct answers are considered acceptable.

Reflection: In case of reflection the angle of incidence should be equal to the angle of reflection
Magnification: The problem involving magnification is solved correctly if the following statement is true:

$$N = \left|\frac{b}{v}\right| = \frac{\text{Image Size}}{\text{Object Size}}$$

With magnification *N*, object distance *v* and image distance *b*.
Lens formula and focus: When calculating focus point, the image size and object size the following statement should be true:

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{b}$$

With focus distance *f*, object distance *v* and image distance *b*.
Snellius law: A problem involving refraction is solved correctly if the following statement is true:

$$\frac{\sin i}{\sin r} = n$$

With angle of incidence *i* angle of refraction *r* and refractive index *n*. When using this formula the refractive index depends on the wavelength of the light. The refractive index to be used when the light goes from a material to air is the inverse from the one listed in reference guides.

Step 4: Design supportive information
Design the non-recurrent information and design the way it is presented in game. The supportive educational design can be updated from existing material.

The supportive educational information consists of the following strategies for solving physics problems. It includes finding the variables in the description of the exercise, choosing the right formula for the problem, using the formula and solving equations.

The game is targeted towards exam students in the last year of high school and assumes the students already possess skills such as calculating the missing variable in a formula and solving equations. As such this information will not be presented explicitly. However the game will guide the player using tutorials and "Hints and Tips" as described below.

The supportive gaming information is the following:

- Genre: Puzzle - advanced point-and-click adventure
- The goal of the game is to guide a moth caught in a magical 2D world to freedom, solving physics puzzles and problems on the way to escape back to the 3D world. These puzzles take the form of calculating or adjusting the path of light using the physical properties of the objects in the game environment. The moth will then follow the light to freedom.
- Problems will be described by the moth himself or the creatures in the 2D world. To solve these problems the player has to follow the following steps:
    - Determine the physics problem presented in the game
    - Find the necessary variables
    - Find the right formulae and laws needed to solve the problem
    - Solve the problem and continue to the next level

This information is provided in different ways. The genre itself is not explicitly mentioned, but determines the way the game is played. The goal is presented in the form of an introductory movie and in the form of in-game dialog. The player will be taken through the problem solving process in the form of tutorials for the first few levels.

Step 7: Design procedural information
Design the recurrent information and design the way it's presented in game. This can be updated from existing material.

The procedural information can be divided into two parts. Procedural information concerning the material, which consists of physics laws and formulae, algorithms and physical properties of different materials, and procedural information concerning the gameplay, like using the interface.

Optics
The formulae and laws of physics used in this game are already discussed in section 3.2.1.Optics also makes use of physical properties such as critical angle and refractive indices. The ones used in the game are the following.

	687 nm (red)	589 nm (yellow)	486 nm (blue)	434 nm (violet)	Critical angle 589 nm (yellow)
acetone		1.359			47.4
alcohol (ethanol)	1.359	1.362	1.366	1.371	47.2
benzene	1.494	1.501	1.513	1.520	41.8
cedar oil		1.51			
ether (ethoxyethane)	1.350	1.353	1.357	1.361	47.7
phosphorus in carbondisulphide	>1.95				<31
glycerol	1.466	1.469	1.475	1.480	42.9
kitchen salt solution (1 mol L^{-1})		1.38			46.4
carbon disulphide	1.615	1.628	1.652	1.677	37.9
tetrachloromethane		1.466			43.0
water	1.330	1.333	1.337	1.341	48.6
diamond		2.417			24.4
refractium	1.22	1.54	1.85	2.15	40.5

Procedural gaming information for this game is the following.

Controls
The player has to solve puzzles using a couple of different tools to adjust the physical properties of objects in the game environment as well as measure and set features such as the angle of the light. These tools are the following.

- **Move**: Some objects in the game environment are movable. Using this tool they can be moved to different positions
- **Rotate:** Some objects can be rotated. This tool rotates them clockwise using the left mouse button and counterclockwise using the right mouse button
- **Lens strength:** The strength of a lens can be adjusted using this tool. Click and hold left mouse button to increase lens strength, right to decrease lens strength
- **Measure angle:** Using this tool the player can measure the angle of inclination.
- **Set angle:** Using this tool the player can set the new angle of the light by clicking and entering the angle the light should have.
- **Show hints:** Shows the hints, tips and extra information provided by the moth and other creatures in the paper world to help with the puzzles.

Some of the puzzles require the player to enter an answer. In this case an “answer box” will appear after the question is asked. In this box, the player can type the answer followed by pressing Enter.

<u>Information</u>
Information in this game is offered to the player in several different ways.

- **Hint box:** At the start of each level a text box will appear telling the player what to do in that level. It will provide the player with both supportive and procedural information such as how to solve the puzzle and how to play the game.
- **In game reference guide:** The reference guide contains all prerequisite knowledge in the form of the refraction indices and critical angles of different materials that appear in the game, as well as an overview of all necessary formulae. This reference guide is a direct extract from the BINAS. This is a reference book used by all Dutch high schools and is allowed to be used during the state exam.

In the game environment will only change if the player changes it. If the player gives a correct answer, the player will progress to the next challenge of that level or advance to the next level.

Step 10: Design challenges and levels
Design levels and sublevels dividing the learning tasks up into playable levels with sub-goals
In this step I’ll design the challenges the player will encounter in each level. The goal of each of these challenges is to achieve the correct answer and continue. There is no “half” good answer.

I choose to make 8 levels. This allows me to create the level structure I decided on while still keeping in mind my limited time frame.

As described in step 2 the game will have the following structure:

1. Getting to know the game and interface. Playing around with basic principles (level 1-3)
2. Test and practice all skills in separate exercises with help, based on existing exercises from the optics curriculum (level 4-7)
3. Combine skills with little help (level 8)

The following part will describe all levels starting with a short description of the level and how to finish it. After that i will give a short description of the learning tasks, supportive and procedural information presented to the player in that level. The descriptions are short and refer to the information already provided in the corresponding steps.

<u>Level 1:</u>
Description
A projector shines a beam of light into a cave. The goal is to make the light beam reach the end of the cave which will make a flower grow that will then show the way to the next level. To do this the player will have to

rotate the projector and find mirrors hidden in the dark. These mirrors can then be rotated to reflect the beam of light in a new direction finally reaching the end of the cave and completing the level.

Learning tasks:
Law of refraction.

Supportive Information
Show the basics of the game. Show how to use tips to help solve the problems.

Procedural Information
Angle of inclination is equal to the angle of reflection.
A description on how to use tools and the hint box to solve the challenges in the game
Explanation of how to interact with interactive parts of the game environment
How to use the rotation tool

<u>Level 2:</u>
Description
A big eye cannot focus. The player should move around a lens and adjust its strength to focus on a bird showing the way to the next level. To do this the player has to use construction lines to help the eye focus. The better the player focuses the bird for the eye the clearer the bird is visible. Each time the bird is fully in focus the bird flies to the next spot until finally, after 4 times it reveals a switch that opens the path to the next level. This amount will practice the skill without making the task to repetitive..

Learning tasks:
Lens formula
Focus points and construction lines

Supportive information
Description on how to focus a lens
Reminder on the basics of how to use tools and available information to solve problems.
To focus a lens you can change the distance to the object, image and/or the lens strength

Procedural information
Lens formula
How to create construction lines
How to use construction lines to focus
How to use the move and lens strength tools

<u>Level 3:</u>
Description
The player is underwater with a beam of light breaking on the water surface. The beam however breaks in a wrong way. The player has to look up the refraction index of water and calculate the right angle of refraction the light should have. After the right angle is entered the beam of light reveals the way to the next level.

Learning tasks
Snellius law and refraction

Supportive information
Show the need for looking up the right formulae and values in the reference guide

Procedural information
Explain how to use the in-game reference guide

Explain how to use the answer box
Step by step guide to using snellius law to calculate the angle of refraction using the reference guide and incoming angle

<u>Level 4:</u>
Description
The player is in a ship with multiple reflecting fish. A clamp shines a beam of light that has to find its way toward the exit of the ship. To finish the level the player has to use the angle of reflection to calculate and draw the path of the light reflecting of the shining fish towards the end of the level.

Learning Tasks
Law of Reflection

Supportive information

Procedural information
Law of reflection
Explain the use of the Measure Angle tool
Explain the use of the Set Angle tool

<u>Level 5:</u>
Description
The player is in a cave with a big crystal made of the imaginary material refractium. The player has to calculate and draw the path a beam of light will take through the crystal. The yellow light breaks and the player should calculate the breaking of each of the four different colors for which refraction indices are defined. When the path of all colors has been calculated and drawn the resulting rainbow of colors melts the ice, opening the way to the next level.

Learning Tasks
Snellius Law and refraction
Different wavelengths

Supportive information

Procedural information
Explain how to use the Measure and Set angle tool in combination with Snellius law to determine the path each color of light will take
Explain how to switch between colors in the game

<u>Level 6:</u>
Description
A monster blocks the player’s path. The player has to scare the monster away by creating a magnified image of himself using a big water drop as a lens. The player will have to calculate the focal distance, the image distance, and the magnification of the image. The image will then be created and the monster flees, revealing the path to the next level.

Learning tasks
Magnification
Lens Formula

Supportive information
How to solve a lens problem (presented in the step-by-step questions)

Using formulae and using multiple formulae to calculate the unknown variable

Procedural information
Lens formula
Magnification formula

<u>Level 7:</u>
Description
The player arrives in a pipe system. The way is blocked by jets of liquid. These jets can only be stopped if the player labels each of the pipes with the right name of the liquid it is spraying. To do this the player has to measure the angle of refraction of the light going through each of the jets, calculate the refraction index and look up the corresponding liquid. When each of the jets is properly labeled the way is clear to proceed to the final level.

Learning tasks
Snellius Law and refraction

Supportive information
Using formulae to calculate the unknown variable

Procedural information
Snellius Law
Refractive indices of the liquids

<u>Level 8:</u>
Description
The player arrives in the forest with a huge diamond in the moonlight. The player has to calculate the path of the moonlight through the diamond using refraction and reflection and keeping in mind the critical angle of diamond. The moonlight finally shows the way out of the 2D paper world the player is trapped in, allowing them to escape and finish the game.

Learning tasks
Snellius Law and refraction
Mirror law
Critical angles
Use of different wavelengths

Supportive information
Using formulae to calculate the unknown variable

Procedural information
Snellius Law
Mirror Law
Breaking index and critical angle for diamond

These levels together cover each of the learning tasks and include the supportive and procedural information designed in the previous steps. It has an increased focus on the more difficult tasks such as solving problems that include refraction using Snellius Law.

3.2.3 Develop

Now that the design is finished, I develop the implementation of the game. This includes creating an artistic style and programming the game itself. For the artistic style my very good friend and gifted artist Anastasia Stebakova helped me out. She has designed the environments and characters while I animated and implemented the game. Together we designed the interface.

As platform for creating the game itself I use Game Maker 8.1 by YoYoGames. This program offers a wide variety of tools for creating games, especially in 2D. Its many tools allow for fast prototyping, while its powerful scripting language allows for altering almost any aspect of the game.

The interface

Figure 5 shows the interface of the game.

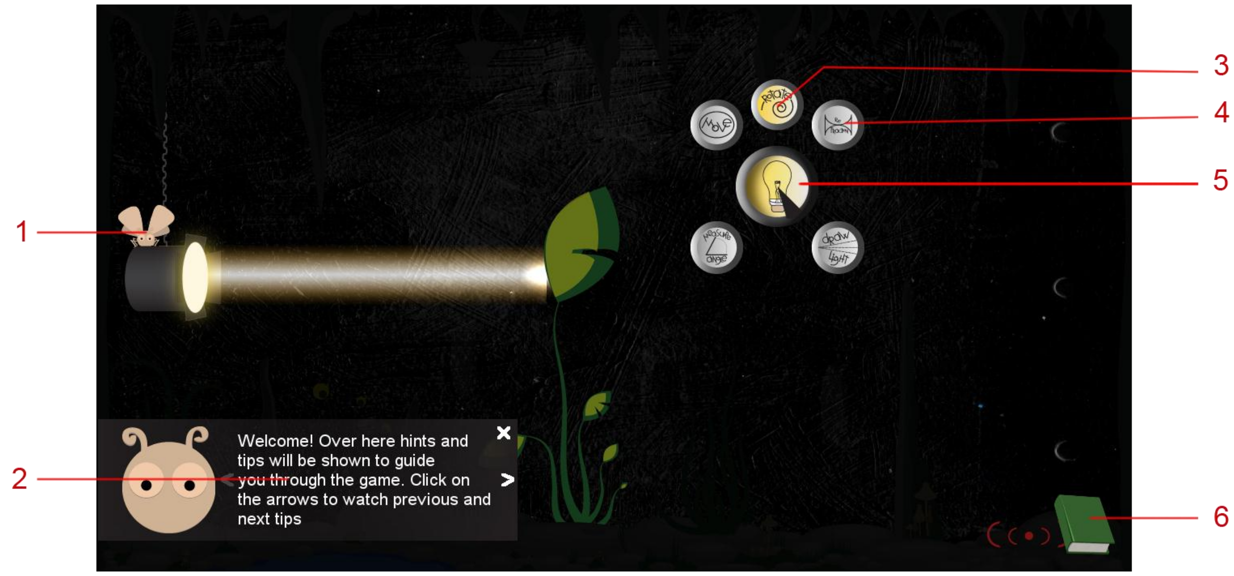


Figure 5: Interface moth

1. The moth, the main character of the story
2. Hint and help box. This box supplies the hints tips, and explains what needs to be done in each level
3. Active button. Tools that can be used have colored buttons.
4. Inactive button. Tools that cannot be used this level have greyed-out buttons.
5. Radial menu. Click the middle mouse button to access the tools; Move, Rotate, Lens strength (refract), Measure angle, Set Angle (draw light). Click the middle button in the Radial Menu to show the Hint and Help box.
6. Reference book. It contains all formulae, refractive indices and critical angles needed in this game.

The Reference Book

This is a direct extract from BINAS, the Dutch reference book on physics, biology and chemistry. It is used by all schools and allowed at the state exam (see figure 6).

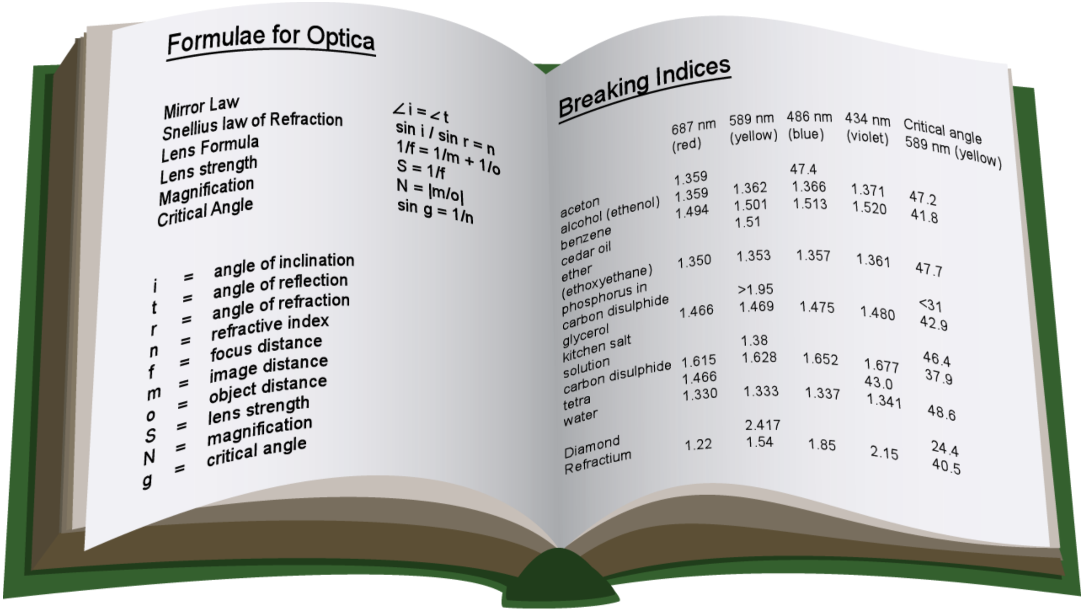


Figure 6: In-game Reference book

Levels
The levels themselves were created following the design made in the Design Phase. Extra levels are included as in-game cinematics to show the transition from one level to the next. However they have no other function than aesthetics. See Appendix B for screenshots of each level.

Release Platform
GameMaker allows for multi-platform development. I want to make the game available on both Windows and Mac OSX. However, the Mac OS edition of GameMaker is one version behind the windows version and not compatible. This made it impossible to create an OSX compatible version without rewriting most of the game.

Languages
The game supports both English and Dutch gameplay.

Animation Movies
The talented 3D artist Anton Bondarenko created two animation movies for this game. One introduction and a final movie for when the player finishes the game. The introduction movie shows the moth being captured in the magical 2D paper world. The final movie shows the moth bursting out of the paper and flying free again..

Music
The music used in this game is composed by Kevin MacLeod (incompetech.com). MacLeod's wonderful music is free for use in any project provided the right credits are given.

3.2.4 Implement

Now that the game is developed it is time for the implementation, deploying the game in the user environment. Of course the game was tested internally first to remove the major bugs. Then the game was released by making the game available on a website for download on https://sites.google.com/site/yarentertainment. Apart from a download link this site also contains a cheat-sheet for people who cannot figure out a challenge. This cheat-sheet first explains how to calculate the answer in each challenge before finally giving the answer.
I decided to supply this cheat-sheet to allow all players to finish the game and play all levels. This will give them the possibility to finish the game and experience all levels. This way everyone can comment on the game as a whole and find any bugs that might exist in later levels even when they cannot figure out a challenge. On this site there is also a link to a survey for feedback on the game (see section 3.2.5 Evaluate). The game is also made available on the school PC in a VWO level school in Zeist. The students were given the opportunity to play and evaluate the game.

3.2.5 Evaluate

The Survey
To gather feedback on the game I created a survey. The survey is supplied with the game on the website (see section 3.2.4 Implement). It asks the test subject to rate the game on multiple aspects of gameplay, the interface, appearance and educational value on a scale of 1 to 10. Apart from the grade, the test subject has the possibility to give extra written feedback on each of the aspects. See Appendix C for the complete survey.

Test Subjects
The game was tested by two types of test subjects; the target group consisting of exam year VWO students and other interested people, mostly university students who already passed the exam. Both test groups played the game and answered the same questions in the survey.

Results
I received only a small amount of feedback, from a total of 12 people in the form of survey and 2 people gave direct feedback using email. While the game was made available both for download at home and on the school computers, it seems that students are not that interested in working on school in their free time. This could be helped if the teacher would integrate the game in the teaching process. In spite of the low number of responses, the feedback that I did receive can still be used to improve the game.

I will analyze the gathered feedback on each of the aspects covered in the survey separately.

<u>Gameplay and Interface</u>
Feedback was rated on several different aspects. It is clear what to do in each challenge (average of 7.6) and how to accomplish that (average 7.8). The supplied hints and tips were considered clear and useful (average 7.3), and the game was considered rather fun to play (average 6.9). People were motivated to finish the game (average 8.7). However the game scored much worse on pacing (average 5.8) and length of the game (average 5.2). Elaborating on the rating given, test subjects noted that the game feels slow and is too short.
The user interface is not easy to use (average 5.1) nor is it clear where to click to use the environment (average 4.6). People noted that using the middle mouse button to make the tool selection appear is annoying to use, and not available on all systems. While interacting with the environment it is not always clear where to click. The place to click is often a bit higher or lower than one would naturally expect them to be. The use of language however was given a good rating (average 7.8), with the exception of a few spelling mistakes.

<u>Appearance</u>
On appearance the subjects rated both overall style (average 8.2) and the 2D art (average 8.4). The choice of music (average 7.9) was appreciated. Both the in-game animation and the introduction and final animation were

rated fairly good as well (average 6.5 and 7.6 respectively). Test subjects noted the style is beautiful, clear and unique.

Educational Value

The game was designed to be a tool for practicing optics for students who already know the material and have to practice it for the state exam. It comes as no surprise that the game rated very poorly on teaching students new material (average 4.2) while having a very high rating on the aspect of practicing known material (average 8.8). It also helps increase the feeling of insight of the test subjects (average 7.9). However it scores very low on the difficulty curve (average 4.3). The game is very easy at the start, and suddenly becomes much more difficult instead of smoothly increasing in difficulty. It does not seem to especially motivate the test subjects to learn more physics (average 6.0).

Conclusions and Improvements

In this section I will discuss the feedback and propose improvements to be made in the next round of the design process.

Gameplay and Interface

It is clear that the pacing and length of the game have to be adjusted. The game is too short and needs extra gameplay. To remedy this more levels should be added. An idea for a level could be calculating the path of starlight through a telescope (including both lens and mirror laws).

The second thing that should be looked at is the pacing. Playing the game feels slow and sluggish while playing. There are several ways this could be fixed. One of them is to include better rewards for fulfilling subtasks. While many levels have sub challenges in the form of answering multiple questions and calculating the path of light, the rewards for doing this correctly are minimal, usually in the form of a small animation. This makes the game feel slow. Rewarding these accomplishments should increase the sense of progress and make the game feel faster and more rewarding.

Improving the interface will help with this problem as well. If the player is fighting against the interface it will remove any momentum from the game and slow down the progress. Accessing the tools should be easier. One possibility is to allow access to the tools using the number keys and allow scrolling through them using the mouse wheel. Of course it has to be clear where to click to interact with the environment and all specific comments on this will be used to adjust the interaction.

Appearance

People seemed to be happy with the style and appearance of the game. So I will not change this in the next round of the design process.

Educational value

It is good to see that the game accomplishes the goal of practicing known material rather than teaching new. It is also positive to see that even though it is not directly tested, the subjects report having an increased feeling of insight. A clear negative point is the difficulty curve. The game starts out easy and then suddenly becomes much more difficult. The problem is in the fact that the game goes from playing around with optics in one level to diving fully into Snellius Law in the next. While the player is assumed to know how to solve the challenges, it is not a good transition and gives the game a choppy feeling. To solve this problem should stay closer to the order of difficulty set in step 2 of the design phase. In the game I don’t have an introduction to Snellius law and the first time it is introduced in the game it is immediately used in a complex manner. Also the position of this level in the sequence of levels does not correspond to the sequence given in step 2. A new level will be designed to introduce Snellius law in an easier setting and the first level it is introduced in currently should be moved further in the game.

Other adjustments
In the evaluation I did not get as many responses as I had hoped for. To obtain more feedback in the next cycles I should work more closely with the teacher and school. I will also approach multiple schools and physics teachers, giving me a larger test group. Working closer with the teachers will also allow me to time the evaluation better and get a better impression on how the game will work when integrated in the curriculum instead of given as an extra option.

In conclusion, in the next round of the design progress I should look at step 2 for the correct sequence of difficulty, step 3 for better rewards and step 10 for designing extra levels. I should also contact more schools and teachers to get a larger test group and integrate the game more smoothly with the planned curriculum.

4. Conclusion and Future Work

In conclusion my work provides a solid method to create educational games. It helps collecting all the necessary data and it helps collecting all the information the student needs while playing the game and learning the material it offers.

I am by no means a professional game designer and a lot of the feedback I got in the evaluation phase, such as the bad learning curve and slow pacing of the game, can be explained by my lack of experience in this field. During the making of Moth I found that by using this method I already had a complete overview of all that was needed and how it should be combined to create a game. This was reflected in the feedback. While there are negative points that need improving the information provided was not one of them and the learning goals were clear.

To improve on my work I would like to see my method used in a larger project. While the case study presented here functions as a proof-of-concept it is a one man operation. For further validation of the 5/10 method it should be adopted in a larger project involving a larger and more experienced game company. It will show how this method fairs when used by more than one person at a time and how well it integrates with existing teaching methods on a larger scale.

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Appendix A: Learning goals, tasks and background information

Learning Goals

1. Know and use Refractive Index and Snellius Law
2. Know and use the Law of Reflection
3. Know and use the lens formula, including being able to calculate and use focus points, lens strength and use construction rays for a positive lens.
4. Calculate with magnification using the magnification formula
5. Know that different wavelengths of light (and as a result different colors) have different refraction indices.

Learning Tasks

1. Correctly calculate the refractive index, angle of incidence or angle of refraction using Snellius Law
2. Correctly Calculate angle of incidence or reflection using the Law of Reflection
3. Correctly use construction rays and focus points in problems involving positive lenses
4. Correctly calculate magnification, image distance, object distance, image size or object size using the Law of Magnification
5. Correctly use the right refractive index based on the color of the light.

Needed procedural information

1. Refraction

Refraction is the bending of light when it moves to a different medium with a different optical density. The degree to which this happens depends on the refraction index of the medium.

	687 nm (red)	589 nm (yellow)	486 nm (blue)	434 nm (violet)	Critical angle 589 nm (yellow)
aceton		1.359			47.4
alcohol (ethenol)	1.359	1.362	1.366	1.371	47.2
benzene	1.494	1.501	1.513	1.520	41.8
cedar oil		1.51			
ether (ethoxyethane)	1.350	1.353	1.357	1.361	47.7
phosphorus in carbon disulphide	>1.95				<31
glycerol	1.466	1.469	1.475	1.480	42.9
kitchen salt solution (1 mol L^{-1})		1.38			46.4

carbon disulphide	1.615	1.628	1.652	1.677	37.9
tetrachloromethane		1.466			43.0
water	1.330	1.333	1.337	1.341	48.6
diamond		2.417			24.4
refractium	1.22	1.54	1.85	2.15	40.5

- Angle of refraction (r), angle of incidence (i) or refractive index (n) can be calculated using the following formula:

$$\frac{\sin i}{\sin r} = n$$

- Refraction index from for light going from the material to air is the inverse of the refraction index of light going from air to material as shown by the formula:

$$n_{B \to A} = \frac{1}{n_{A \to B}}$$

- Critical Angle is the smallest angle of incidence at which a light ray passing from one medium to another less refractive medium can be totally reflected from the boundary between the two.
- Critical Angle (g) can be calculated, given refractive index (n) using the following formula

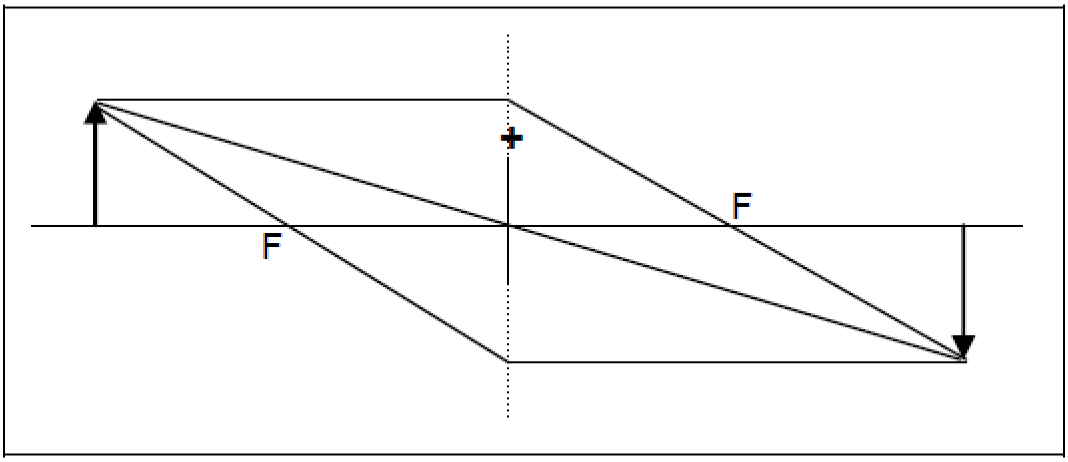
$$\sin g = \frac{1}{n}$$

- Refractive index for light with longer wavelengths (red) have smaller refractive indices than those with smaller wavelengths

Reflection
Angle of incidence is equal to the angle of reflection

$$\angle i = \angle t$$

Construction rays
- construction lines are made by drawing lines using the following rules:
  - a light ray going through the optical centre of the lens continues unchanged through the lens
  - a light ray going through the focal point **before** entering the lens continues parallel to the lens axis after the lens
  - a light ray parallel to the lens axis before entering the lens will go through the focal point behind the lens



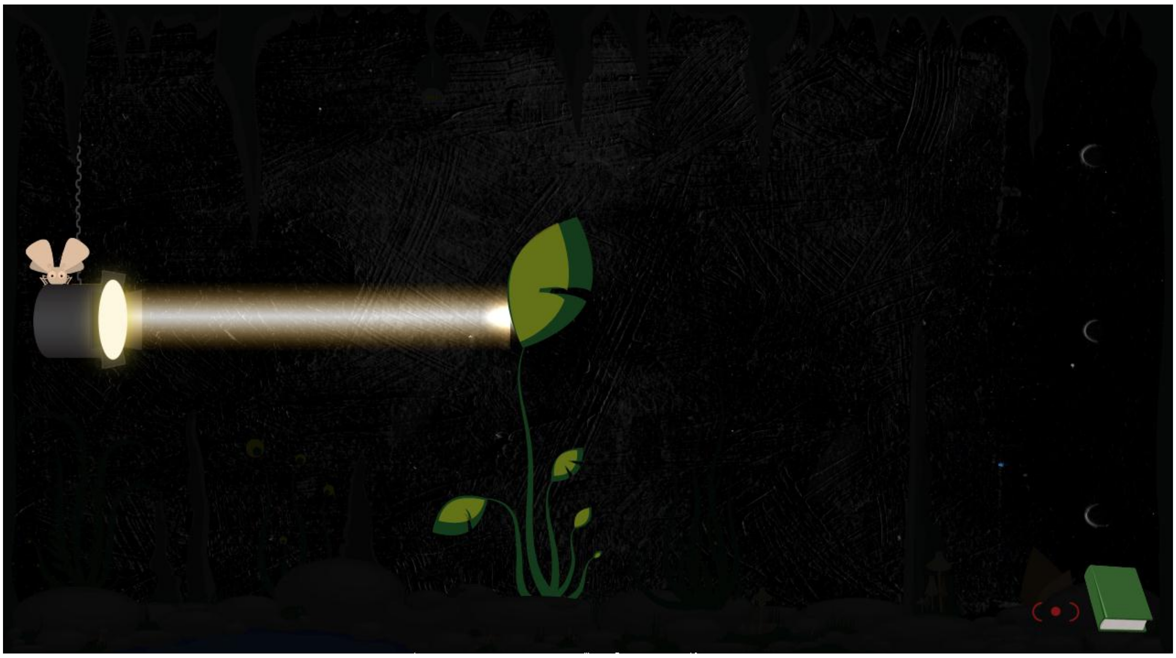
Magnification

Magnification is image size divided by the object size as well as the absolute of image distance divided by object distance

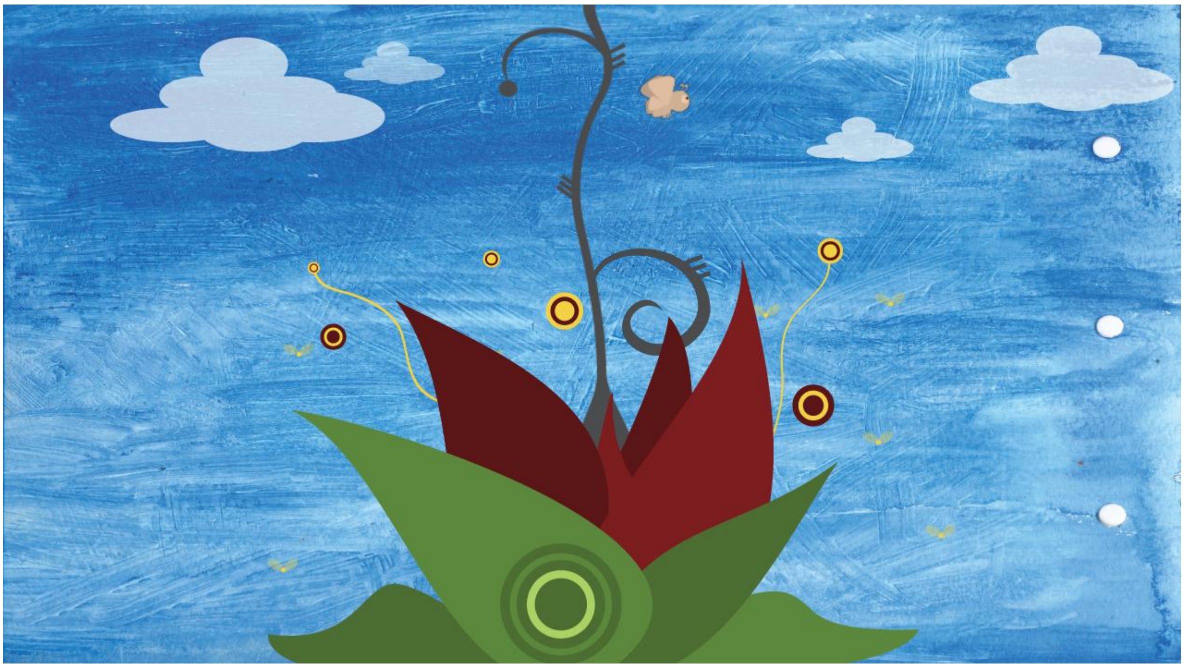
$$N = \left|\frac{b}{v}\right| = \frac{\text{Image Size}}{\text{Object Size}}$$

.

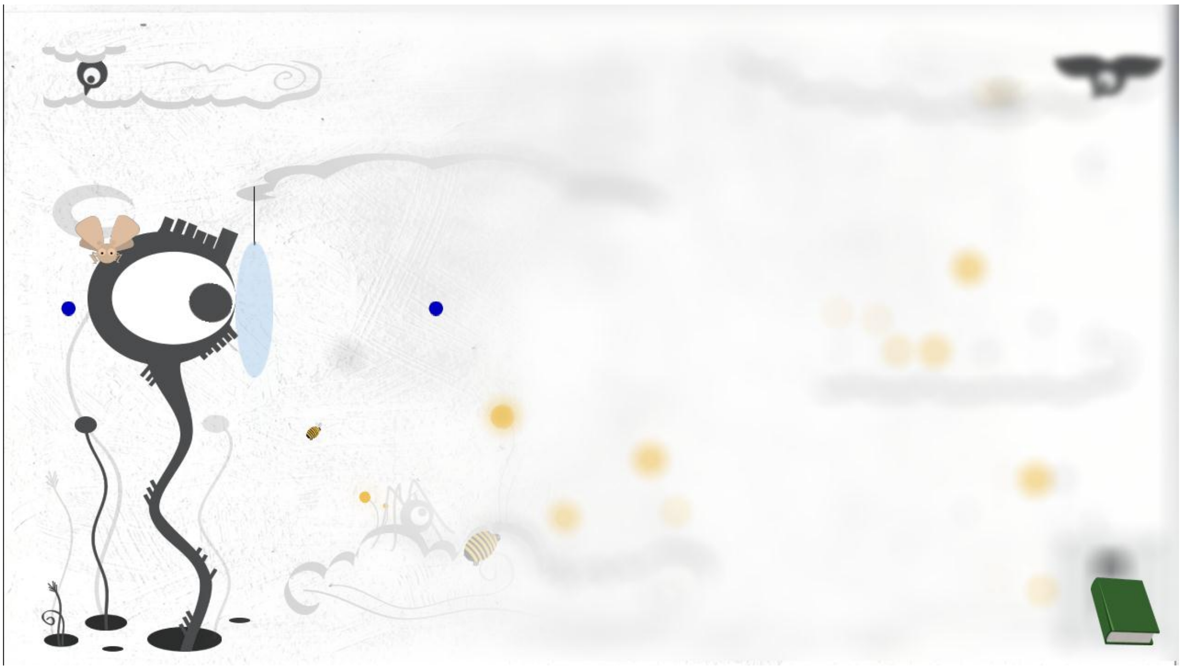
Appendix B: Level screenshots



Level 1, Mirrors in the Dark



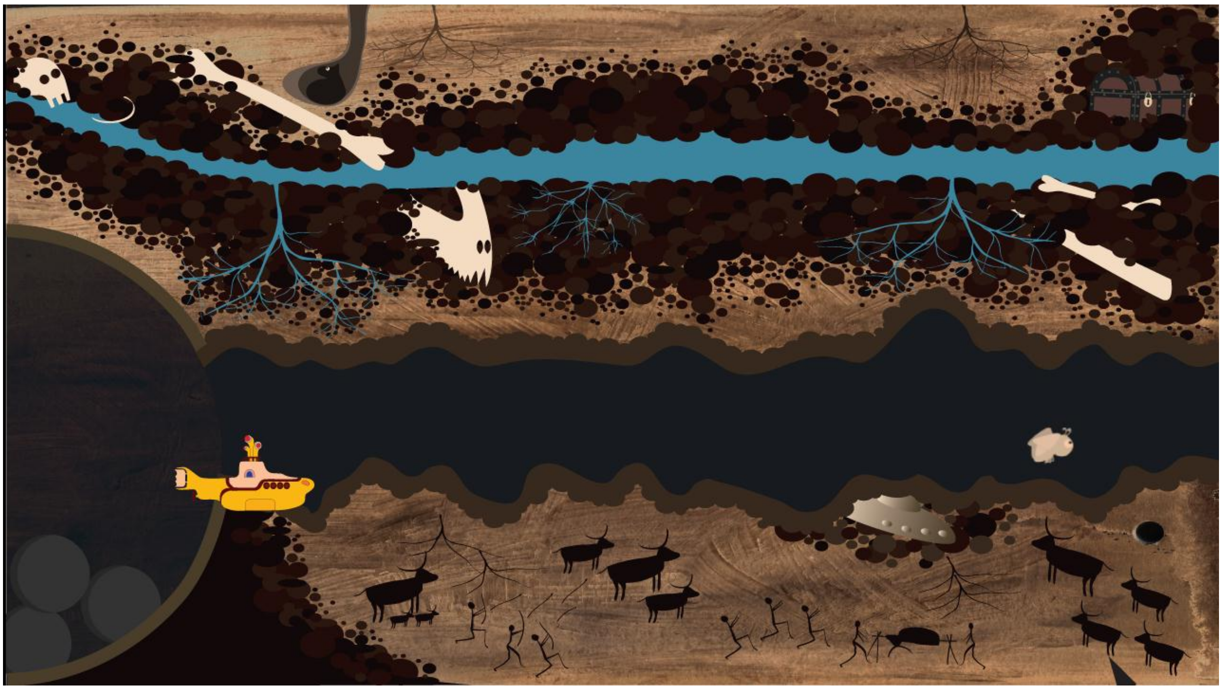
Transition, The Flower Grows



Level 2, Eye in the Sky

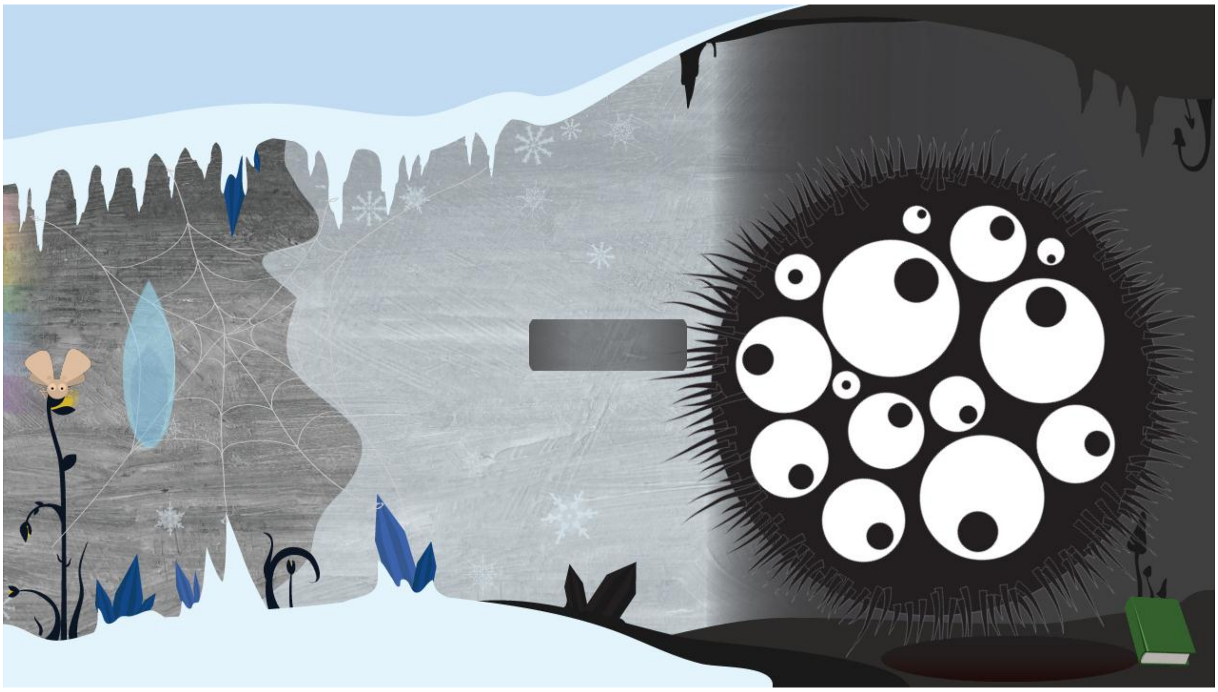
Level 3, Liquid Luminosity

Level 4, Mirror Fish

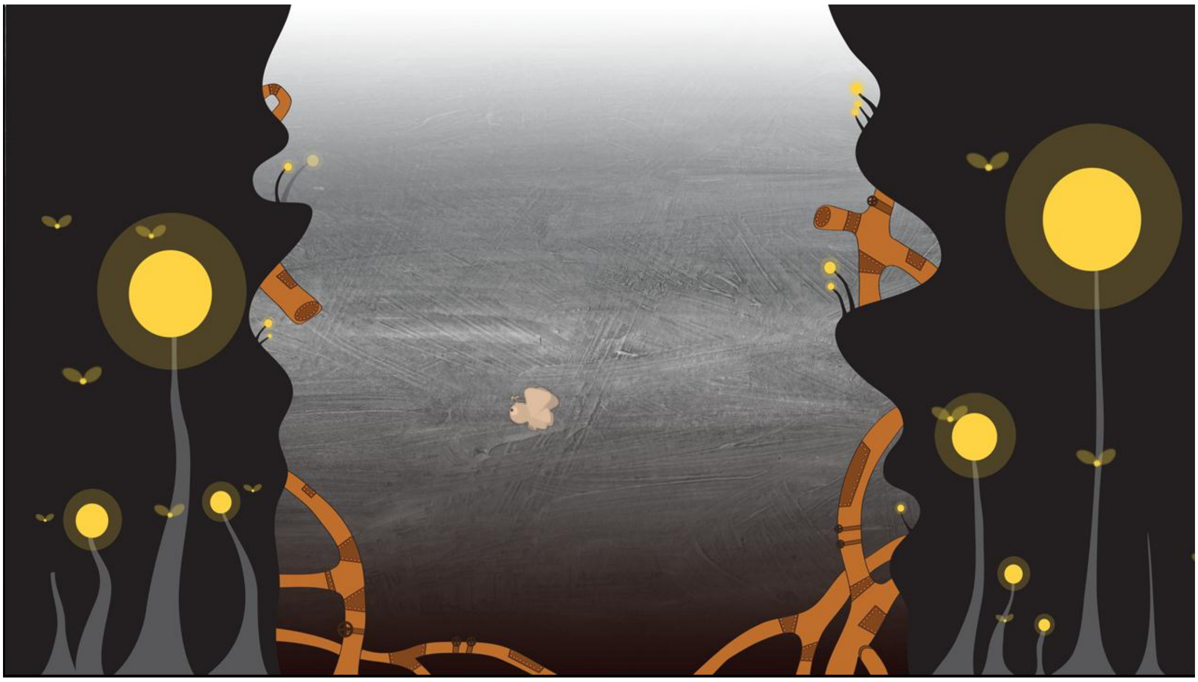


Transition, Out of the Ocean

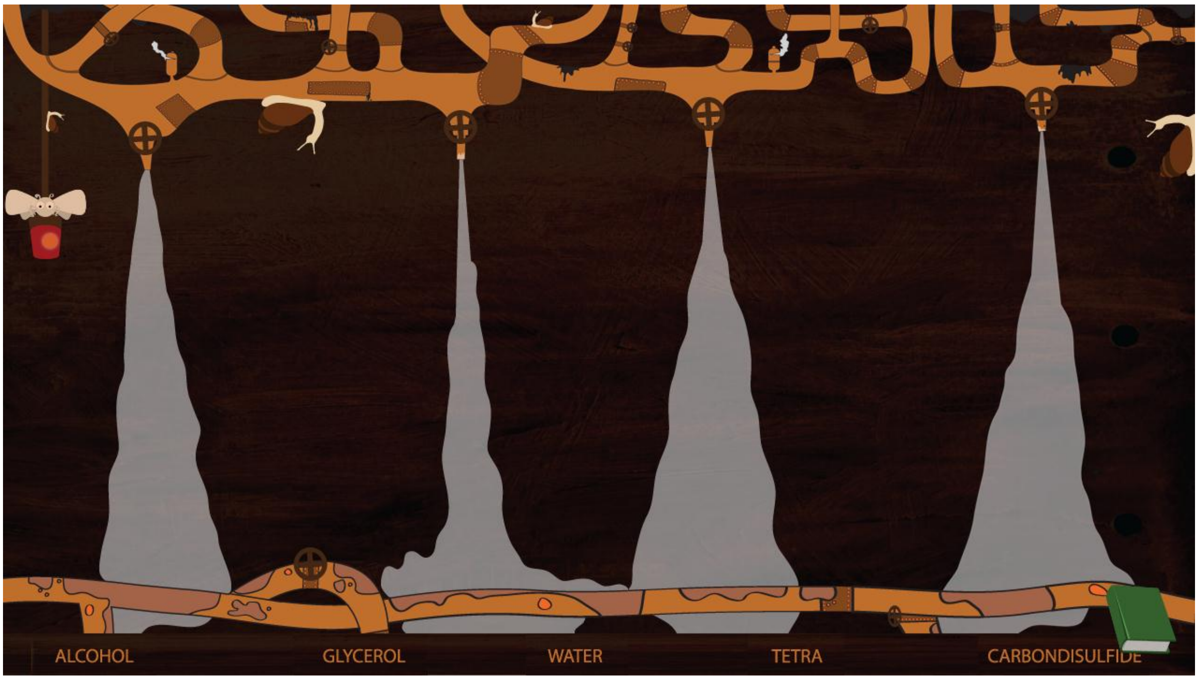
Level 5, Prism Practice



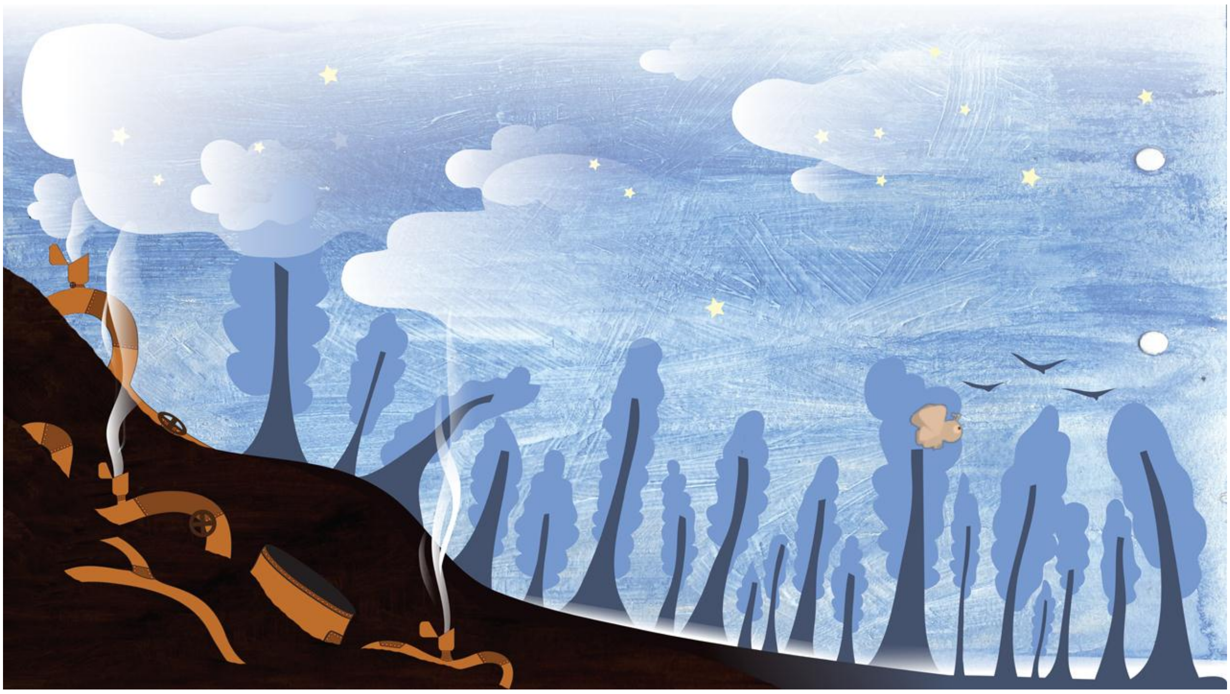
Level 6, Scary Images



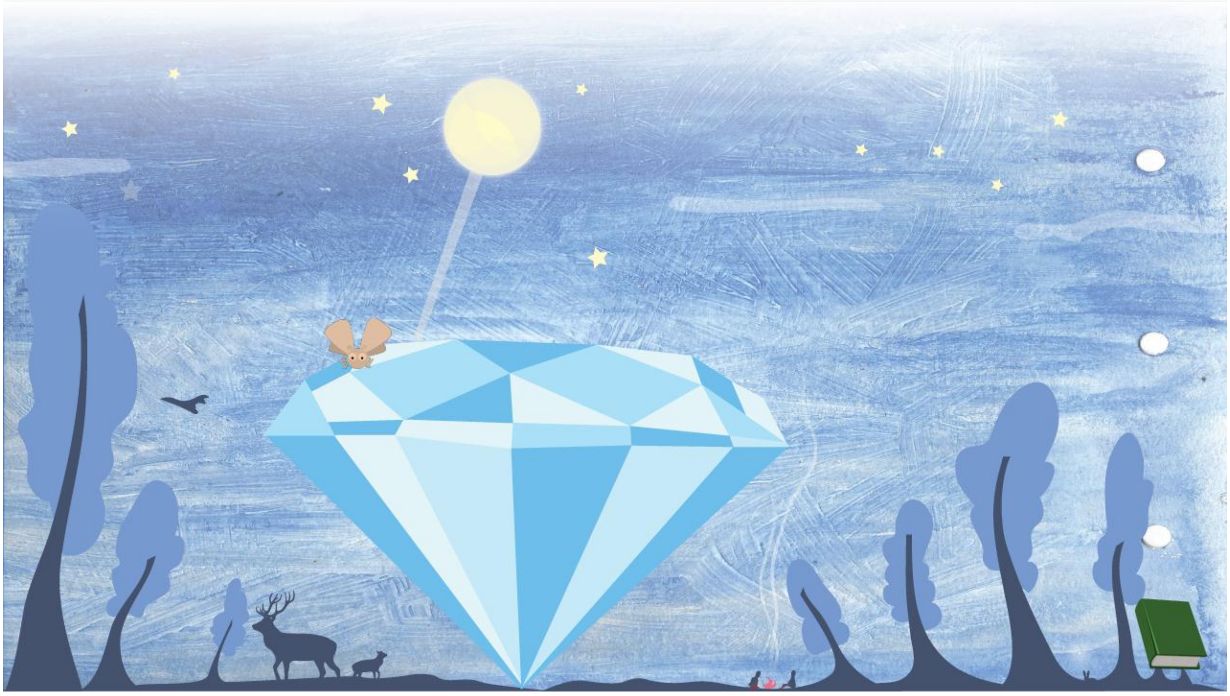
Transition, Down the Hole



Level 7, Pipe Dreams



Transition, Out of the Pipes



Diamonds are Forever

Appendix C: The survey

This is the English version of the survey presented to the test subjects. The survey was done online.

Welcome

Thank you for participating in the survey. In this questionaire I will ask you to rate different aspects of gameplay, looks, interface and the educational value of the game on a scale from 1 to 10, followed by the option of clarifying your choices with remarks and suggestions. Even though it is optional to clarify your choices, suggestions and critique will greatly help me in my thesis and in improving the game and will be greatly appreciated.

The survey will take about 5 to 10 minutes.

Personal Information
Current Education (or last education if not in school)

VMBO
HAVO
VWO
HBO
WO
Other, please elaborate

Gameplay
Please rate each of the given aspects of gameplay on a scale from 1 (lowest) to 10 (highest)

Clarity on what to do
Clarity on how to do it
Clarity of the hints and tips in the bottom left
Pacing (A game with good pacing doesn't go too slow or too fast)
Entertainment (How fun is it to play the game)
Length of the game
Motivation to finish the game

Please elaborate your choices (optional)

Look and Feel
Please rate each of the given aspects of the look and feel of the game on a scale from 1 (lowest) to 10 (highest).

Overall style
2D artwork
In-game animations
Intro and ending animation video
Choice of music

Please elaborate your choices (optional)

Interface

Please rate each of the given aspects of the interface on a scale from 1 (lowest) to 10 (highest)

Ease of use of the interface
Clarity on where to click and when
Placing of the interface elements
Clarity of use of language

Please elaborate your choices (optional)

Educational Value
Please rate each of the given aspects of educational value of the game on a scale from 1 (lowest) to 10 (highest)

The ability of the game to teach you new material
The ability of the game to help you practice know material
The steepness of the difficulty curve (low rating means the game gets too difficult too fast or stays too easy for too long)
Improving your understanding of optics
Improving the motivation to learn more about optics or physics.

Please elaborate your choices (optional)

Please describe your idea of what you learned in this game.