DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics: Games Engineering

Elementary – Serious Game for Discovery of Chemical Elements

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Elementary – Serious Game zum Kennenlernen der chemischen Elemente

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Submission Date:	15.10.2019

I confirm that this master's thesis in informatics: games engineering is my own work and I have documented all sources and material used.

Munich, 15.10.2019 Benjamin Braun

Abstract

Games with a crafting or gathering aspect tend to help the players remember the processes and recipes after a while. This paper attends the development of a serious game in which this concept is used to convey real-life knowledge about the chemical elements. The rather simple goal is to collect all 118 elements, but the processes of obtaining them are closely based on the real world. The players can discover all elements, their sources and usages, and a number of chemical compounds, materials and ores on the way to complete the periodic table in this UI-based serious game.

Contents

1 Introduction

In order for a game to be classified as a serious game, it needs to have a primary purpose other than entertainment [MC05], but within this definition, the boundaries are quite vague. Simulators, training modules and educational quizzes represent one side of serious games, with a clear strong focus on imparting information and education, but sometimes these applications forget the other side, and second part of this term: game.

The main reason for the education to take place within a game is to support the learning process by making it an intrinsic part of the fun within 'play'. As described by Johan Huizinga in "Homo Ludens" [Hui38] and summarized in [MC05], 'play' is defined with six characteristics:

- Voluntary: "play to order is no longer play"
- Pretend: "play is not 'ordinary' or 'real' life"
- Immersive: "taking up the player's full attention"
- Limits: "played out within certain limits of time and space"
- Rules: "it creates order, is order"
- Social: "creating a social group of the players or tending to cause people involved in a particular kind of play to identify themselves as a group"

Furthermore, games might be a "higher form" of 'play', as described by Huizinga [Hui38]. The absence of the keyword 'fun' in these definitions can be explained by 'fun' not being an ingredient, but rather the result of a game [MC05].

While serious games tend to violate one or more of these characteristics, especially often times not being voluntary, having fun is still a very important part and desired result of serious games. This is what makes them a successful educational method, making the learning process part of the fun in playing a game.

For this thesis, another extreme within the umbrella term 'serious game' will be given attention to: A serious game which is first and foremost just a game for entertainment purposes. The educational aspect comes in a very subtle way. The game uses real world information and knowledge to make up its rules and mechanics, therefore in understanding how the game works and successfully playing it, the player will, in theory, automatically gain knowledge about the relevant topics. Of course with this kind of method, the learning process is not very suitable for important topics requiring precise information to be imparted. The knowledge gain is much more passive and vague, which makes this approach better suited for broader information and the expansion of the player's basic knowledge.

The topic chosen for the game of this thesis, chemical elements, is fitting well for this kind of game. The idea of doing a serious game in that field even stems from a similar experience of gaining knowledge unintentionally from a game with no educational purpose, purely the usage of the game's mechanics caused the player to passively learn about real life (See Chapter 2).

The information obtainable from this game about chemical elements is ranging from facts about them, where and how they are obtainable, what they can be used for, to what kind of machines and other resources are used in the processes. None of it is vital knowledge, the game is not precise enough to help for example students in chemical fields, but it provides a pool of information where interested players can 'dive' in and explore, all while primarily playing a game, and secondarily learning real life facts passively on the side.

This game is experimental and quite on the border of the term 'serious game', trying to examine how effectual this type of passive learning can be, if the focus strongly lies in the actual game aspect of serious games.

As mentioned earlier, the knowledge inside this game is vague enough to only really be applicable to interested individuals as a target group. People who enjoy exploring the nature of elements, minerals and chemical processes are most likely to learn from this game, since the personal interest and motivation should create fun in learning and make it easier to absorb knowledge.

The main goal of this thesis is to ascertain what kind of content and methods are necessary to have an adequate learning effect in a game that does not present itself as a serious game. For this examination the components of abstraction of real life complexity, balance of game-play fun and realism, as well as immersion of exploration are especially crucial.

To gain insights on these details, the thesis will give an in-depth look on how the relevant information about the chemical elements was compiled and how it was transformed into a base of data useful for a game, the idea and structure of the game, as well as issues within the implementation and findings about ways around them.

2 Related Work

Since this thesis is looking at games with a very subtle serious learning aspect to them, the amount of games which would fit this kind of classification is pretty high. The topic of chemical elements is also a very often utilized aspect of games, especially within the crafting and gathering genre.

Instead, this section will firstly take a closer look at the inspirations for the idea for this game.

2.1 Inspiration

One of of the most popular and well known crafting games is of course "Minecraft"[1] (by Mojang AB, 2011). The game itself only has marginal relation to chemical elements, for example only iron and gold are obtainable, and the process of obtaining them is far from any real world methods and extremely simplified.

But the game is a well-used platform for modifications ('mods' for short), which are user-developed additions and changes to the game. Some of them add more resources to the game and increase the complexity of machinery, technology and processes, which makes the game far more interesting for the topic of this thesis' game.

Playing with certain mods installed sparked the initial idea for a serious game about collecting all chemical elements, and so the most important mods will be presented in more detail.

Minecraft Mod "Mekanism"

The mod called "Mekanism"[2] by Aidan Brady adds a variety of technology and machinery to Minecraft, complete with its own resources, which are mostly selected chemical elements.

The processes used to obtain certain resources are more complex than in the base game, and actually resemble the real world quite accurately in many cases. So can hydrogen and oxygen be gained by putting water in a machine called "Electrolytic Separator"; sodium and chlorine come from separating salt, which in turn can be

[1] `https://www.minecraft.net`

[2] https://aidancbrady.com/mekanism/

obtained by evaporating water to brine, and so on. Many real life correlations are portrayed in this mod and make the player very curious to explore and learn about the processes and connections.

The one specific experience, which led me personally to the idea for the game of this thesis, was how I learned to produce sulphuric acid. Mekanism allows the player to get more gain from metallic ores than normally possible in Minecraft by putting the ores through a more complex multi-step processing chain. An important component for this is to dissolve the ores in sulphuric acid before washing out the resulting ore slurry and further processing it into pure metals. The challenge is to produce all necessary ingredients, like the acid, and build the machines for it. The production of sulphuric acid is done with another chain of processes, namely oxidizing sulphur to sulphur dioxide (SO_2), further infusing it with oxygen to sulphur trioxide (SO_3), and then finally infusing it with water vapor to create sulphuric acid (H_2SO_4) (See Figure 2.1 and 2.2).

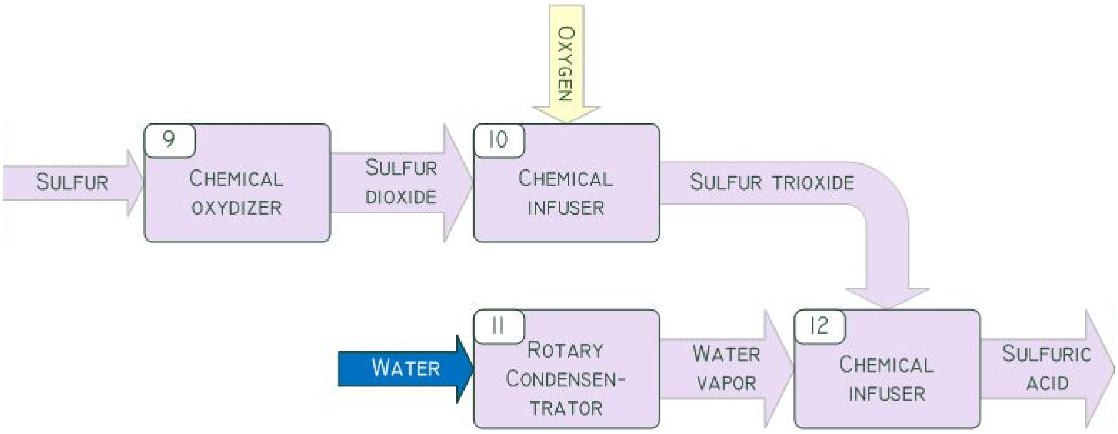

Figure 2.1: Flowchart for sulphuric acid process in Mekanism[3]

While the machines and some of the recipes might be a little simplified to fit the nature of the game, the process is very similar to the industrial standard of manufacturing sulphuric acid [Sei].

Realizing how close to the real world the in-game method is, and how much I already learned because of looking up the process for the game, spawned the idea for this serious game. If a game can motivate players to learn methods, processes and facts for advancement inside of the game, then real life knowledge will be gained passively if only the game represents the real life accurately enough.

The mod Mekanism is most likely not meant to be teaching about real world chemistry, and there are still a lot of very simplified and inaccurate processes in the game,

[3] https://wiki.aidancbrady.com/w/images/aidancbrady/0/09/Mekanism-flowchart.png

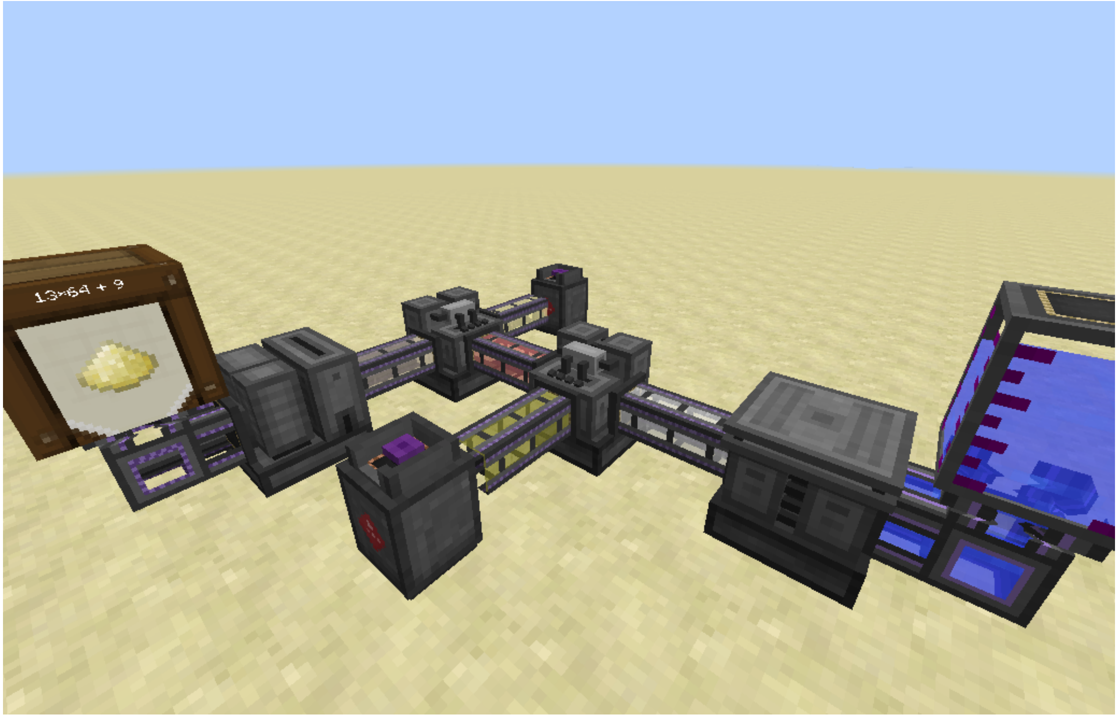

Figure 2.2: An in-game screenshot of a simple production chain for sulphuric acid in Mekanism

but the fact that for some of the features the mod unintentionally fulfills the role of a serious game, as in players gaining knowledge from it, is astonishing and definitely interesting for research in the methods of passive imparting of knowledge.

Minecraft Mod "MineChem"

Another relevant mod for this thesis is "Minechem"[4] by jakimfett and TheRealp455w0rd. It adds every chemical element up to Number 113, Nihonium (further elements were not yet discovered at the time of developing the mod) to Minecraft, along with a big number of molecules. Some elements can be obtained by deconstructing certain items into its relevant molecules and those further into their raw elements, for example cellulose ($C_6H_{10}O_5$) amongst others can be extracted from any plant-like item, which then can be split into carbon, hydrogen and oxygen.

While this mod respects the realistic components of any item and molecule, and is as such quite informational in a different way, the processes of obtaining said components

[4] `http://iopleke.github.io/Minechem/`

is in contrast to "Mekanism" extremely simplified. Extractions happen in a single simple machine called "Chemical Decomposer", no matter the item, and the "Chemical Synthesizer" is able to put together any item from its respective compounds with no further complication.

Furthermore, some elements are not obtainable from molecules or items in Minecraft, so they can be produced by fission or fusion in their respective chambers. This process is also not very realistic, because it only relies on mathematics with the atomic numbers of the elements in question. For example, chromium, atomic number 24, can be produced in the fission chamber by putting in cadmium with atomic number 48, which simply gets divided by two and results in two chromium. In the fusion chamber, chromium can be produced by putting in any two elements which atomic numbers add up to 24. These methods are of course only theoretically correct in the real world and most times highly unfeasible.

Even though the mod oversimplifies most methods of obtaining elements, which is the main focus of knowledge in the game of this thesis, the whole concept of having all elements available and respecting the compounds of every item and molecule is very relevant to the topic. On top of that, MineChem encourages the collection of all elements (See Figure 2.3), which is the main motivational goal of "Elementary", the game of this thesis.

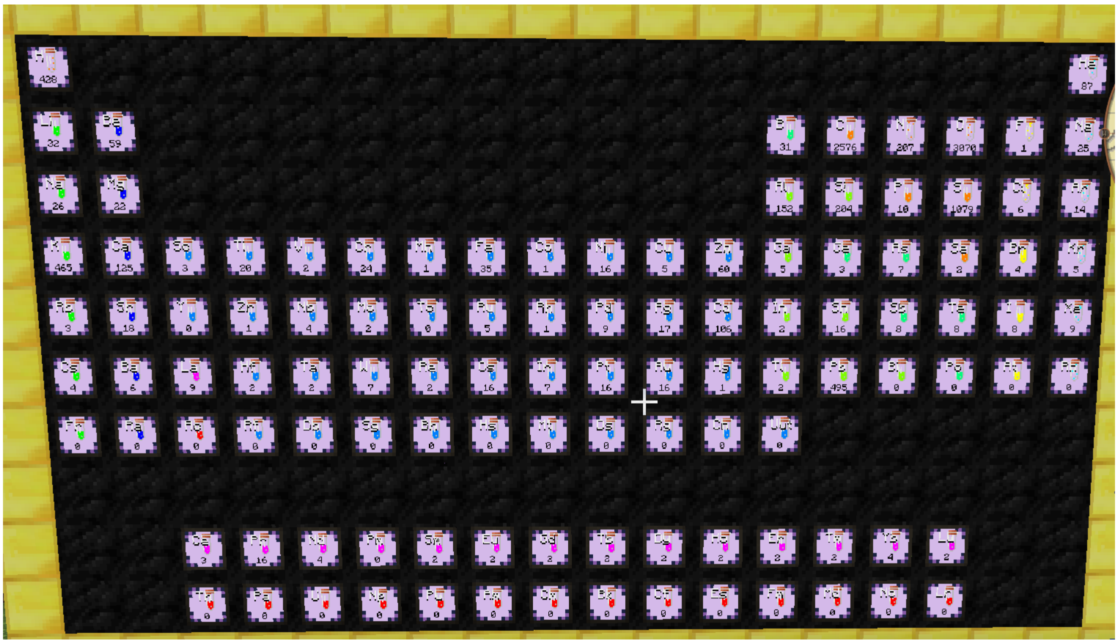

Figure 2.3: An in-game screenshot of a completed periodic table in MineChem

Both Minecraft mods presented here bring certain aspects to the table that are highly relevant and interesting. The combination of those aspects and the reforming into an appealing game with high realism and motivational learning effect is the essence of the idea that spawned from playing Minecraft with those mods.

2.2 Topic-Related Serious Games

On the topic of serious games for chemistry, elements, and the periodic table, there are several smaller examples of what has been usually done in that field. Even though this thesis has a different approach to the issue and disassociates itself from the typical serious game used to teach pupils about a certain subject, it is important to look at those examples to see the extend of their covered subject matter.

The search for serious games about the periodic table shows that quizzes about trivial facts are most common. It seems to be very popular to have the player either guess the symbol of the element by their name or vice versa, find the correct place in the periodic table to a given element, or fill in blanks in the periodic table. Games like "The Periodic Table" on Funbrain[5], several quizzes on Sporcle[6], or "Periodic Table Game" on Sheppard Software[7] represent this style of short online trivia quizzes very well, and show the abundance of this type of serious game.

The game "Sortify: Elements of the Periodic Table" on Brain Pop[8] uses at least more than just symbols and names to challenge the players, sorting according to atomic numbers, category, electrons, or properties of the element are also enquired.

To mix it up, there is also a strategy board game called "Periodic: A Game of The Elements" from Genius Games[9], which lets the players discover several facts about the elements, while moving across the periodic table as a playing board. Movement is done within certain aspects of the periodic table, such as being only able to move in direction of increasing atomic mass or increasing ionization energy. One objective is to collect the corresponding elements to a goal card, signifying certain uses of elements, for example components of organic life or alloys of steel. This game seems to have the widest range of informative facets to it from the games presented so far, and combines scientific accuracy with board game fun.

[5] https://www.funbrain.com/games/periodic-table-game
[6] https://www.sporcle.com/games/tags/periodictable
[7] https://www.sheppardsoftware.com/periodictable_0_click_common.html
[8] https://www.brainpop.com/games/sortifyelementsoftheperiodictable/
[9] https://www.geniusgames.org/products/periodic-a-game-of-the-elements

As said initially, these kind of serious games are quite different to the thesis' game idea, which does not have its main focus on teaching about small facts about the periodic table or the elements, although this type of information is also available in the game.

2.3 Real-Life Collections

The motivational goal of the game "Elementary" is to collect all elements and complete the periodic table. While this goal is a logical corollary for the topic of the game, it was also inspired by element collections in real life. This hobby can have reasons of scientific interest, or just be a pastime for the joy of completing a collection. Such a display can also make for an impressive piece of decor.

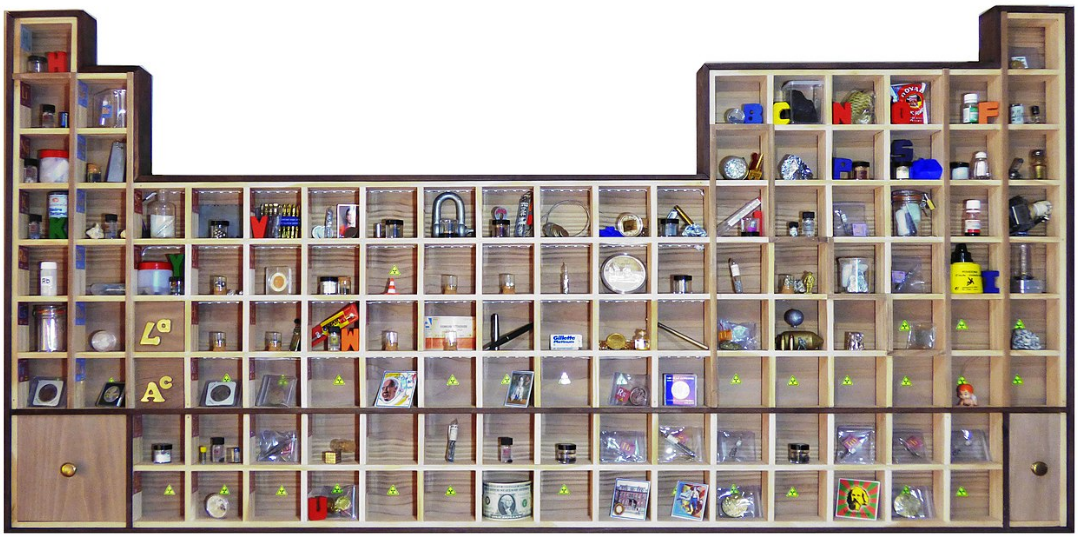

Figure 2.4: A display of a collection of elements[10]

Some collectors attempt to only collect high purity samples, while others see compounds or alloys as acceptable too, along with mineral samples or items containing the elements. There are also differences between the collectors trying to find or extract the elements on their own as best as possible, and those just buying sets of them, which is possible in many ways, for example from established specialist providers online, such as `https://www.novaelements.com/` or `https://118displays.com/`. This hobby can be quite expensive and potentially protracted, depending on the methods used [Gra].

[10] `https://en.wikipedia.org/wiki/File:Wooden_periodic_table.jpg`

Of course some curtailments have to be made, as most of the heaviest elements are highly radioactive and often too short-lived to be displayed, others are highly toxic, such as arsenic or thallium, or too reactive, such as caesium or fluorine, and therefore restricted in sales. Finally, some elements are simply extremely rare and difficult to find or adequately expensive. Except for the extremely radioactive and short-lived elements, the extra challenges can nonetheless be mastered by dedicated collectors.

The motivation of periodic table collectors hopefully translates into the game to provide an interesting goal and an incentive to explore each of the elements, while having none of the risks and all of the possibilities.

3 Research

The topic of chemical elements and the periodic table has information to no end to offer. In preparation for this thesis and the development of the game "Elementary", first I had to learn most of the aspects this field of knowledge has to offer, in order to then translate it into suitable knowledge to be imparted in this game.

3.1 Compiling Information about the Elements

The approach used was to begin by informing myself about each individual element in general, then compiling useful facts and researching more about specific details.

For each element, in order of their atomic numbers from hydrogen to oganesson, the journey began with "Periodic Videos", a very informative series on YouTube by the University of Nottingham (`http://www.periodicvideos.com/`). Each element has a dedicated video, in which facts and curious details are explained, with some experiments or demonstrative examples to provide a visual experience as well. The approach of the team behind "Periodic Videos" makes it easy to get familiar with the particular element and pick up on general uses and curiosities about it.

From there, usually I would begin to collect general facts about the element from various sources, mostly Wikipedia (`https://en.wikipedia.org/wiki/Periodic_table`) to begin with. Data like atomic number, symbol, name, category, state of matter, atomic weight, electron configuration, radioactivity and origin of their name is most of the time easy to find and was collected in a spreadsheet, which builds the basis for the database of knowledge used in the game (See Figure 3.1).

On top of that, the most common uses for the element were added to the spreadsheet as well. While not being directly related to the game's content, listing these uses made it easier to assign certain material costs to machines or other resources. Examples would be the use of copper for alloys like bronze and brass, or the importance of zinc for anti-corrosion coating.

The most important and in some cases most work intensive part of research was the sourcing and processing of each element. Since this part of information is the main focus of the game, it was significant to have a detailed explanation of the element's

A	B	C	D	E	F	G	H
Atomic Nr.	**Symbol**	**Name**	**Category**	**State of matter**	**Atomic weight**	**Electron configuration**	**Radioactivity**
							t=Half Life Time
1	**H**	Hydrogen	Nonmetal	Gas	1,008	1	stable
2	**He**	Helium	Noble gas	Gas	4,0026	2	stable
3	**Li**	Lithium	Alkali metal	Solid	6,940	2/1	stable
4	**Be**	Beryllium	Alkaline earth metal	Solid	9,0122	2/2	stable
5	**B**	Boron	Metalloid	Solid	10,810	2/3	stable
6	**C**	Carbon	Nonmetal	Solid	12,011	2/4	stable
7	**N**	Nitrogen	Nonmetal	Gas	14,007	2/5	stable
8	**O**	Oxygen	Nonmetal	Gas	15,999	2/6	stable

Figure 3.1: An excerpt from the spreadsheet used to collect element data for research and the database of the game

main sources and how those source materials get processed into the pure form of the element.

Some elements have many ways to obtain them, for those only the most common or easiest applicable sources where collected. Others have extremely long and complicated processes, for which a detailed description is hard to find. Several different sources were used to try and understand the process enough to put it down in the database, such as:

- Both the English and German version of the element's Wikipedia page
- `http://atomistry.com/`
- `https://www.britannica.com/`
- `http://www.seilnacht.com/Lexikon/PS2.htm`
- `http://www.periodensystem-online.de/index.php`
- `https://www.thebalance.com/metals-and-commodity-trading-4073364`
- `http://www.webmineral.com`

Unfortunately, in many cases the methods on those sites differ quite significantly from each other, even both language versions of Wikipedia had a surprising amount of discrepancy between them.

This led to a necessity of choosing the most applicable and reasonable process, often combining different aspects from several sources, to get a coherent and usable processing chain description for this element. It is possible that the realism for these special cases suffered a little bit, but if extended research can not bring up a better explanation of the sourcing of this element, then this should not be an issue, especially since complex processes get a bit more simplified for the game. The effort to give players a general idea on how elements are processed is still intact.

To give some examples of how simple or complex those processes can be, a few select elements are presented here in the manner of how their sourcing was summarized. In my personal notation parenthesis signify the input to the method used, which is written before like a programming function, for example: Electrolysis(Water) means the method of electrolysis is used on water. Any non-relevant byproducts are not included.

- Hydrogen:

  Electrolysis(Water) = Hydrogen

- Helium:

  Distillation(Natural Gas) = Helium

- Lithium:

  Evaporation(Brine) = Lithium Chloride[LiCl] -> Electrolysis(55% Lithium Chloride + 45% Potassium Chloride) = Lithium

- Beryllium:

  Melting(Beryl) = Beryl Frit -> Sulphuric Acid[H_2SO_4](Beryl Frit) = Beryllium Sulphate[$Be(H_2O)_4SO_4$] -> Ammonia[NH_3](Beryllium Sulphate) = Beryllium Hydroxide[$Be(OH)_2$] ->
  EITHER 1. Ammonium Hydrogen Fluoride[NH_4HF_2](Beryllium Hydroxide) = Beryllium Fluoride[BeF_2] -> Heating(Beryllium Fluoride + Magnesium) = Beryllium
  OR 2. Heating(Beryllium Hydroxide) = Beryllium Oxide[BeO] -> Beryllium Oxide + C + Cl_2 = Beryllium Chloride[$BeCl_2$] -> Electrolysis(Beryllium Chloride) = Beryllium

Even just these first four elements emphasize how vastly different the complexity of processing elements from their source material can be. These examples are already put into a coherent shape from all different kinds of sources, in some cases selecting the most convenient method, in others pieced together from vague descriptions.

The source of elements is hereby not the problem, it is easy to explain that hydrogen can be gained from water, helium from natural gas, lithium from brine or essentially salt water, and beryllium from the mineral beryl. The simple fact about an element's source is of course also included in the game, and much more suited for interested players to look up.

The actual processing necessary to extract the elements themselves are more like bonus knowledge for the very curious. This further signifies why this game is not a traditional serious game, but rather a way to explore information about topics that are exceeding the usual basic knowledge or school subjects.

3.2 Reduction of Real Life Complexity

As seen in the previous section, actual chemical processes to extract elements from their source materials can be very complex, and even though the methods have already been simplified and picked out to an extend in cases with conflicting sources, vague descriptions or too many options, for a game the complexity of real life needs to be reduced.

This is done in several ways:

Machines: All methods used in any of the processing chains of elements or other materials are combined into 16 different kinds of machines. Even though a process would require for example a special blast furnace for a step in iron production, every step is made to fit one of those 16 machines. They are described as follows:

- **Crusher**, used to grind ores and minerals before further processing
- **Evaporator**, a plant to evaporate large amounts of liquid
- **Electrolytic Separator**, a machine simply used for any electrolysis
- **Distillator**, a setup for distilling liquids
- **Dissolution Chamber**, used whenever an object needs to be treated with chemicals, for example acids
- **Reduction Furnace**, for any kind of smelting or reduction steps
- **Roasting Furnace**, for heating processes or burning off materials under oxygen
- **Vacuum Furnace**, for steps taking place in controlled atmospheres

- **Hampson-Linde-Liquefier**, a machine specifically for performing the Hampson-Linde-Process of liquefying air in order to prepare it for distillation into its gas components
- **Oxidizer**, used for treating an object with a gas
- **Ion Exchange Separator**, a machine performing the complex process of separating compounds based on their charge
- **Isotope Separator**, a machine separating different isotopes from the base material
- **Neutron Activation Reactor**, a nuclear reactor for radiating and energizing objects, used for transforming isotopes of radioactive elements
- **Decay Chamber**, a place for radioactive isotopes to safely decay into other elements
- **Cyclotron** and **Linear Particle Accelerator**, for bombarding atoms with particles to form new elements

On top of that, most machines have different tiers, to not only provide upgrading options for the player, but also to include some more specialized versions of those machines. For example, the player starts the first smelting operations with a Smelter, a furnace build from just clay, stone and wood, but can later upgrade to a Reduction Furnace and even an Electric Arc Furnace, all of which perform the same tasks of smelting or reducing objects, just at different capacities and speeds.

While some machines do not exist in this simplified version, for example isotope or ion separation are not done as easily as sticking the components into a machine, the information about the processing step is still preserved and conveyed clearly.

By matching every possible step of all processing chains in the game to one of these functions, the complexity is kept within reason for the game, and the players have an easier time visualizing the methods used on chemical material.

Blueprints: With each processing step being classified by one of the available machines, there was not much possibility to further reduce the complexity of the sourcing chains, without losing the direct reference to the real world processes. That means some of the elements need to have a long and complex production.

In order to not overwhelm players and having them to read up on recipes for those long processes, blueprints are used to help the players tremendously. Blueprints are prefabricated chains of machines, representing one complete process to a specific material being produced from another.

For example, in order to be able to extract nitrogen, oxygen and noble gases from air, the player needs to unlock the corresponding blueprint, use it in the production section of the game, build and insert the machines this blueprint asks for, in this case a Hampson-Linde-Liquefier and a Distillator, and then insert any ingredients needed, which the blueprint asks for as well. If all components are build and inserted, the chain will produce the desired resources.

This system ensures that always the correct order of steps is used for a production chain to work just like in real life and to output the correct resources.

Some processing chains are especially complicated and would be extremely difficult to build without a blueprint. For example the most feasible way to obtain the platinum metals, namely ruthenium, rhodium, palladium, osmium, iridium and platinum, is to extract them from a byproduct residue of copper or nickel processing. Hereby all platinum metals, together with silver and gold, can be won in minuscule quantities from the so called "anode mud" left after purifying raw copper or raw nickel with electrolysis. To get all of the eight precious metals from this byproduct, a number of non-linear steps is necessary to isolate and extract each element, quickly becoming highly complicated (See Figure 3.2).

<table>
<tr><td rowspan="8">Electrolytic Separator (Raw Copper/Raw Nickel) -> Anode Mud</td><td rowspan="8">Dissolution Chamber (+ Aqua Regia)</td><td rowspan="3">Dissolution Chamber (+ FeCl2)</td><td>-> Gold</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Dissolution Chamber (+ NH4Cl)</td><td>Roasting Furnace</td><td>-> Platinum</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Dissolution Chamber (+ HCl)</td><td>Roasting Furnace</td><td>-> Palladium</td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Dissolution Chamber (+ PbCO3 + HNO3)</td><td rowspan="4">Reduction Furnace (+ NaHSO4)</td><td>Dissolution Chamber (+ NaOH)</td><td>Dissolution Chamber (+ HCl)</td><td>Dissolution Chamber (+ NH4Cl + NaNO2)</td><td>Dissolution Chamber (+ HCl)</td><td>Reduction Furnace (+ H)</td><td>-> Rhodium</td></tr>
<tr><td rowspan="3">Dissolution Chamber (+ Na2O2)</td><td rowspan="2">Roasting Furnace (+ Cl)</td><td rowspan="2">Dissolution Chamber (+ HCl + NaOH)</td><td>Dissolution Chamber (+ NH4Cl)</td><td>Reduction Furnace (+ H)</td><td>-> Ruthenium</td></tr>
<tr><td>Dissolution Chamber (+ NH4Cl)</td><td>Reduction Furnace (+ H)</td><td>-> Osmium</td></tr>
<tr><td>Dissolution Chamber (+ Aqua Regia)</td><td>Reduction Furnace (+ H)</td><td>-> Iridium</td><td></td><td></td></tr>
<tr><td>Roasting Furnace</td><td>-> Silver</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Only Copper Anode Mud</td><td rowspan="2">Roasting Furnace (+ Na2CO3)</td><td rowspan="2">Dissolution Chamber (+ H2SO4)</td><td>Reduction Furnace (+ SO2)</td><td>-> Selenium</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Dissolution Chamber (+ H2SO4 + SO2)</td><td>-> Tellurium</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Figure 3.2: Process for extracting platinum metals from anode mud

The blueprint system supports players by presenting the full process at once, with only the machines and inputs to fill in. While there is still a lot of complexity to these processes, the players do not have to concern themselves with it as much, while still maintaining the closeness to the real life.

One last remark towards blueprints, this system allows for any intermediary materials to be cut out completely. The game and the players do not have to concern themselves with the chemical reactions, for example if the roasting of beryllium hydroxide results in beryllium oxide. Blueprints only consider the processing steps one after the other until the relevant output is produced. This allows for further simplification and for the discarding of intermediary products like beryllium oxide, which would only occur in this one step and immediately be processed into other materials.

3.3 Forming the Game Database

With all the research done about every element, facts about them, most common uses and methods of sourcing them, the translation into the game was relatively simple.

Several classes have been created in the game to represent the different aspects:

- **Elements** are identified by their atomic numbers and contain every collected fact as retrievable parameters, along with the blueprint identification numbers which produce this element.
- **Resources** are every material or chemical compound needed for the game that can not be found on the periodic table, such as acids and salts for processing steps, or alloys and materials from nature (for example stone and wood) to build machines. Resources have a separate ID and their uses and source blueprints are saved as well.
- **Ores** classify every mineral that can only be obtained by mining it from the world, and as such they only provide the blueprints that use this ore as input, in contrast to other resources.
- **Machines** are saved with every specification like capacity, energy usage, processing time and so on. Machines that serve the same purpose but are different tiers have the same identification number, along with a tier identifier.
- **Energy Generators**, **Energy Storage**, **Mining Tools** and **Storage Upgrades** are technically machines as well, but each gets a separate class in the database due to differences in parameters.
- **Blueprints** are a special kind of class, designed to hold the information about every step of the corresponding processing chain, retrievable with just the blueprint's identification number. The chains are saved in several parts, each part representing one machine and the process in there, saving inputs and outputs if available, and what kind of machine is needed. With this information the game is able to build the correct process and present the player with the requests for the necessary machines and inputs.

These few classes capture every aspect of research done beforehand and bring the knowledge into the game, ready to be retrieved.

Showing the efforts of the research in numbers, the game database entails all 118 discovered elements; 56 ores, selected from the most commonly used sources for each element that is extracted from minerals; 67 other resources, including chemical compounds, natural materials, alloys, special isotopes and byproducts; 32 processing machines, four mining tools, three storage upgrades, ten energy generators and five energy storages; and a total of 153 different blueprints detailing every production chain in the game.

4 Game Concept

After the intensive look on the research on the elements and how the game's database was formed from it, the focus lies now on the game itself. The idea, concept and development will be examined closer.

4.1 Game Idea

As mentioned in Section 2, the idea for a game about the realistic processes of producing elements originally came from playing certain Minecraft modifications.

The game "Elementary" should provide a platform to explore the world of elements, and be informative without actually actively making the player learn. It is supposed to be a passive serious game, giving the chance to gain knowledge about the real world from just playing and being intrinsically motivated because of own interest.

To achieve this, the game builds upon a discovery system. The goal is to collect every element on the periodic table, and players start out with zero discovered elements. The idea is to have players start by randomly mining in the world map, obtaining certain ores or materials, and by analysing them within the research laboratory function gain knowledge about which elements can be gained from those ores and how to extract them. In most cases this process will require machines or ingredients that the player does not yet possess.

But in discovering those missing materials, new insights can be gained on how to obtain them, until a process is discovered that is already accomplishable. From there the player can collect the corresponding resource, which allows further process chains to function. Obtaining new materials or elements opens up many more sources for other new resources.

The aim is to get the player into a loop of new discoveries, finding out how to obtain the materials necessary to process those resources, and thereby making new discoveries. In the end the player gains every resource necessary to build the most complex machines and obtain even the rarest elements, until the periodic table is filled.

In this general game concept, the player ideally picks up on the processes and sources for the materials and hereby learns more about the world of elements and chemical productions, by just dealing with the realistic processes and being interested to explore.

4.2 Development and Features

The game "Elementary" has been developed in the Unity3D Engine, with the scripting language C Sharp. Designed as a purely user interface dependent game, its visuals are only two-dimensional and resemble most closely a browser game. This concept implies only needing the mouse to play, since all actions are centered around managing resources, using mostly user interface buttons.

The game entails several features aiming at providing an immersive gameplay and the necessary tools to balance fun and information.

Implementing the game was done mostly one feature at the time. At first, the game's database was set up to provide a basis of information, which every script can reference if necessary. After loading a new game, a main menu acts as a gateway towards every other aspect of the game, which as such have been developed separately as different pages.

Following is a closer look on the game's main menu pages, which give a comprehensive overview of all features of "Elementary".

4.2.1 Periodic Table and Lexicon

The game features an interactive periodic table, which simultaneously acts as a way to look up any information about the elements and learn about the periodic table, while also being a tracker for progress towards the goal of the game, to collect every element.

Before an element is discovered, it is marked with a question mark and none of the information about it is accessible. When the element's name has appeared somewhere, for example in a discovered blueprint or as source for any other material, it becomes "known" and a few data points become available. Name, symbol and atomic number will be shown, but any further information requires the player to actually own the element first.

The lexicon closely resembles the functionality of the periodic table, but it has every other resource listed instead, including ores, chemical compounds, and building material. Just as with elements, resources are either "unknown", "known" or "owned" and are marked accordingly, revealing only the corresponding information.

The periodic table features a colour coding system, the elements can be coloured either after their category, which is most common in typical periodic tables, after their state of matter, their radioactivity, or their occurrence in nature. On top of that, each element has an interchangeable piece of information on the element cell in the overview. By default the full name of the element is displayed here, but it can be changed to atomic weight or electron configuration. These help understanding the connections between the order of the periodic table and the element's facts, as well as providing a nice overview to compare (See Figure 4.1).

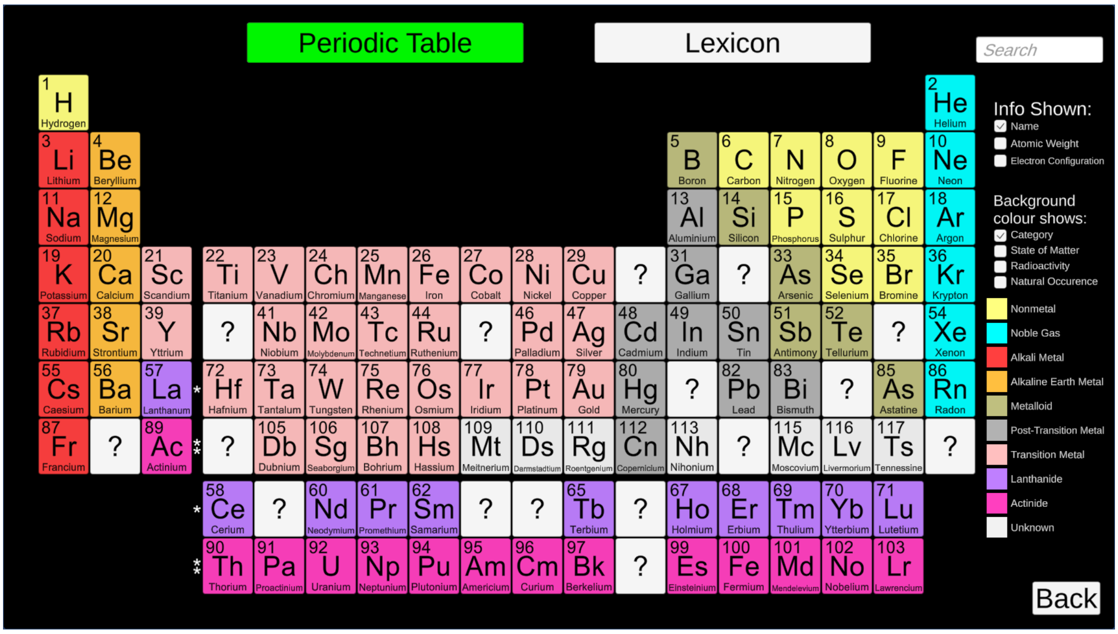

Figure 4.1: A screenshot of the periodic table in game, with some elements still undiscovered

The lexicon, as it is basically a list of all resources, can be sorted in various ways, including alphabetically and by type of the resource. Both the table and the lexicon feature a searchbar as well.

When clicking on either an element or a resource, an info card pops up with every available fact, a picture, links to the sources of the material, and an overview of blueprints producing this element or resource (See Figure 4.2). In case of an ore, the blueprint shows how to process this ore.

4.2.2 World Map

The world map is the beginning point of playing this game. It shows a map of the world, obviously, divided into hexagonal sections (See Figure 4.3). Here the player can "mine" for resources, by clicking on a tile and getting a random distribution of ores and materials common for this area.

The amount of resources obtained is depending on the mining tool used. A pickaxe is available from the start, while pneumatic drills, tunnel bores and mining lasers can be built as soon as the material requirements have been collected, to grant better yield

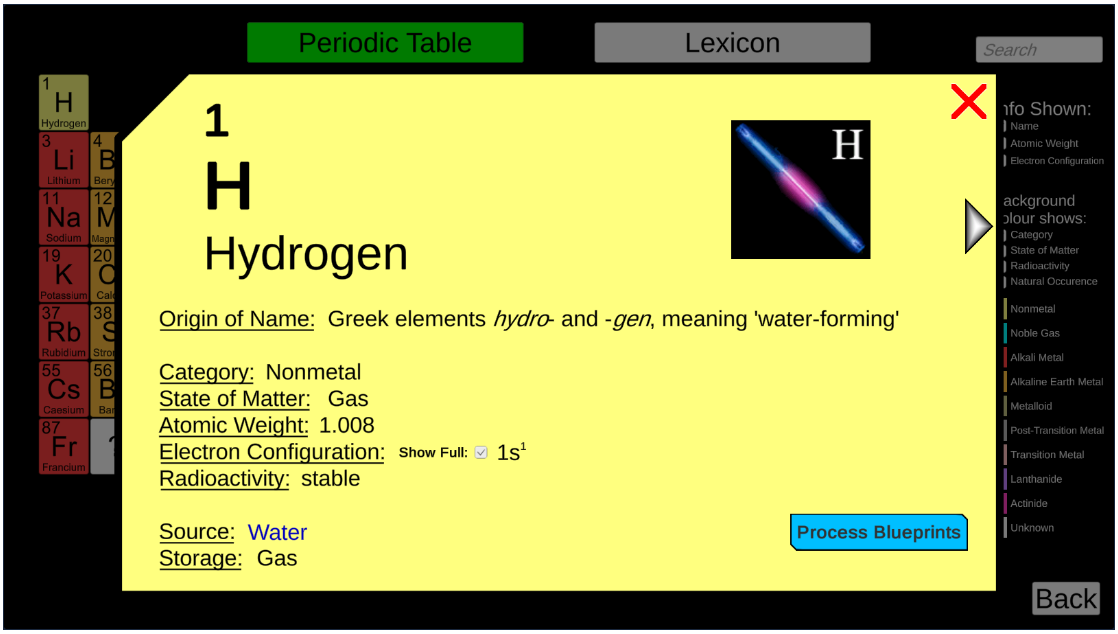

Figure 4.2: A screenshot of the info card for the element hydrogen

from mining operations.

While the random exploration of areas of the world is possible, it can be tedious to look for a specific ore or material. For this issue the world map features a scanner, which lets the player choose from a list of already discovered materials. This includes not yet owned, but known materials, for example if the player discovered the source for beryllium to be the mineral beryl, it is available for scanning.

The scanner marks the most common locations on the world map by colouring the relevant tiles according to the probability of finding the chosen ore.

Hereby excluded are materials which can be found anywhere, like wood, stone, clay, or water. Those can be selected separately, resulting in a "mining" operation which only yields the selected resource.

Another feature to make the player's life easier is the setup of mining outposts. If a player needs a lot of one type of ore, for example monazite, an ore from which rare earth metals can be extracted in tiny amounts, setting up a mine at a specific location on the map with rich occurrences of this ore will continuously produce certain amounts of just this ore. This allows the player to automate certain resource sourcing, in order to not spend half of the play time just clicking on the map to get ores.

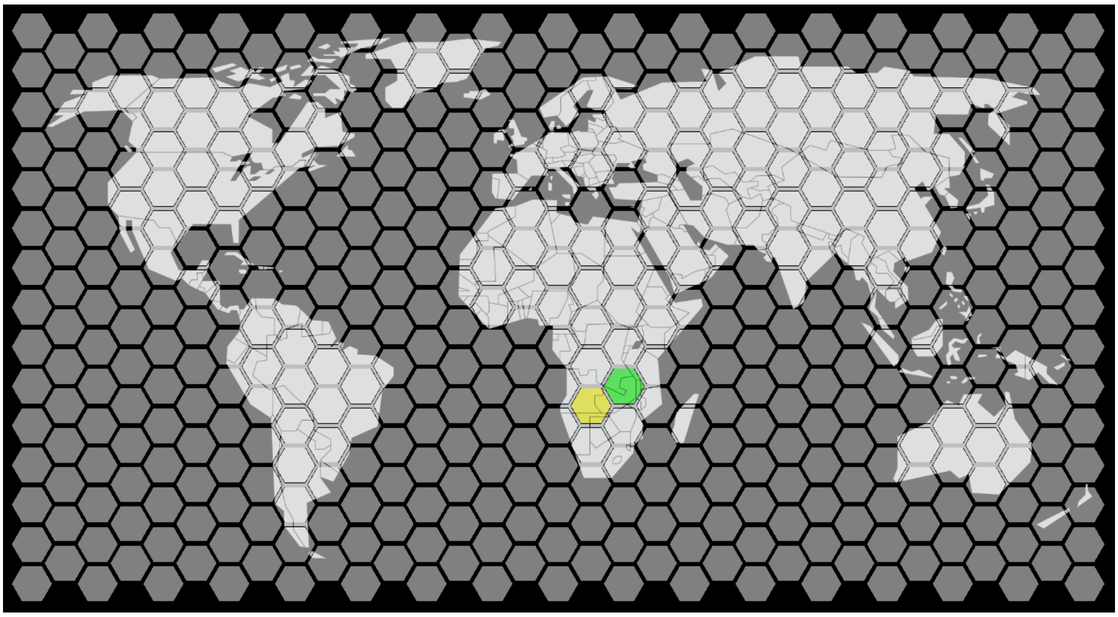

Figure 4.3: A screenshot of the world map for selecting mining areas

4.2.3 Research Center

The research center is a tool for the player to get information and make discoveries that expedite the progress in the game, which is mainly done through uncovering blueprints (See Figure 4.4).

Several different options are available here:

- **Ore Analysis:** Any ore that was randomly obtained can be put into this slot to analyse it. This either shows the elements obtainable from it, if the quick analysis was chosen, or, in case of the intensive analysis, grants access to the blueprints which take this specific ore as input, revealing what kind of elements can be extracted from the ore as well, but providing the possibility to process it on top of that.

- **Specific Research:** This option offers to choose a certain subject to be researched in detail. If an element or a resource is known, it can be researched here to reveal its source and the blueprint for processing that source, thus helping the player obtaining it and progressing further.

  It is also possible to research the construction plans for any machine in the game, which means making the material list for crafting that machine available. It is

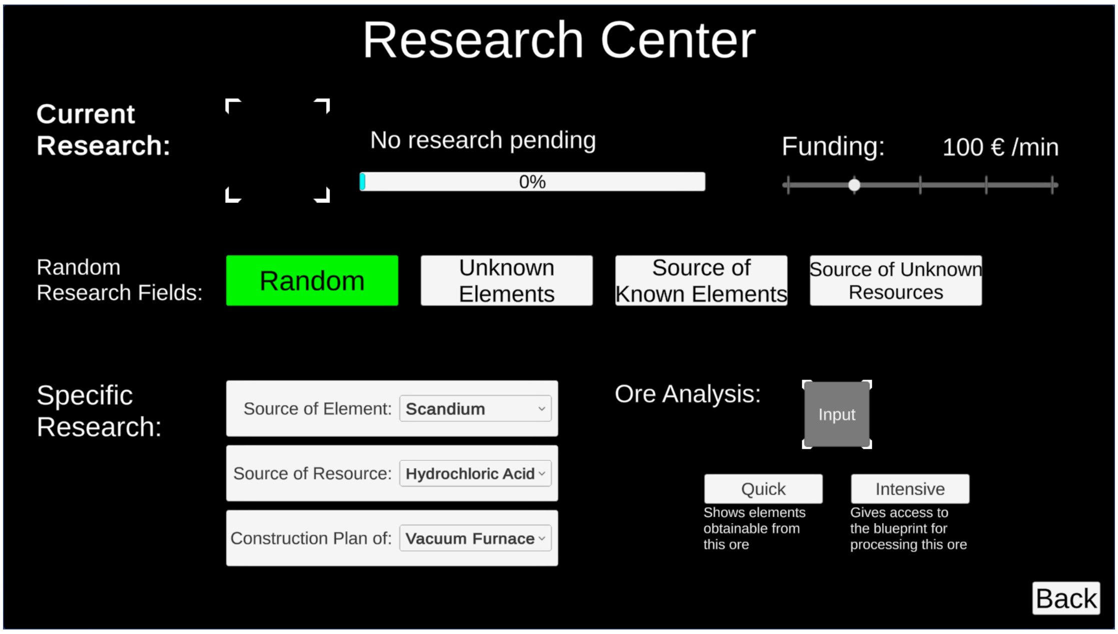

Figure 4.4: A screenshot of the research center

useful to research most of the important machines early on, to gain the options for buying them.

- **Random Research:** This option is, in contrast to the specific research, not directly influenceable by the player, but in turn even more useful. A budget can be set, which changes the speed of the research and can also shut it down. The player can choose from three different topics: discovering unknown elements, granting a random unknown element the status "known" which makes it available for further research; the source of known elements, which, just like the specific research, reveals the blueprint that produces one random not yet owned element; and source of unknown resources, which not only reveals a random unknown resource, but also shows the blueprint of its production. The option to chose none and let the game research from a random topic is also available.

  This random research is a way for the game to prevent players getting stuck. Over time (the random research should be quite slow if not set to a high budget), more and more unknown elements and resources are revealed, together with the corresponding blueprints of the processes to produce them.

These three different ways of gaining more options to progress in the game should make for a dynamic experience, always providing some new aspects to explore and preventing advancement to stagnate.

4.2.4 Machines

This page is a simple overview of all machines in the game. Five tabs group them into processing machines, energy generators, energy storage, mining tools and storage upgrades. Each tab has a list of those machines, showing their names and the current amount in possession. Clicking on a list entry expands the overview and reveals more details about this machine, for example energy usage or capacity, together with monetary and material costs of crafting the machine (See Figure 4.5).

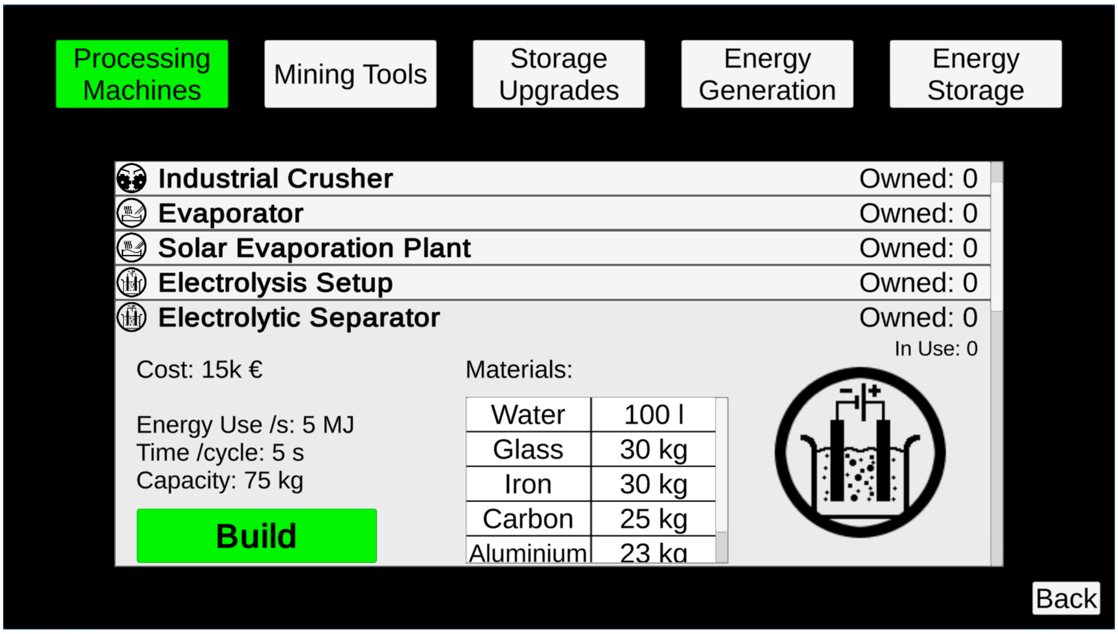

Figure 4.5: A screenshot of the overview page for all machines

- **Processing Machines** are all machines used in blueprints to process materials, such as furnaces, crushers, oxidizer and so on. A detailed description of the different types of processing machines can be found in Section 3.2.
- **Energy Generators** produce the necessary energy to run progressing machines. Several different generators are available to build, which for one provide more ways to actually use the collected elements and resources, but also act as some form of progression system, as generators get more and more expensive to build the more advanced they are.

Most types of energy sources are represented, from coal and gas burning plants, wind turbines, solar farms, hydroelectric plants, to radioisotope thermoelectric generators, nuclear power plants, and even a fusion reactor. The rising demand for higher energy production, as more and more energy intensive machines get built, calls for the exploration of the more expensive and complex generators to keep up with increasing energy costs. Since the higher tier generators also require rarer elements, another incentive is created to keep up progressing in the game.

- **Energy Storage** describes different types of batteries and capacitor banks to store any energy that is not immediately used up by other demands. This allows for some very energy intensive machines, like particle accelerators, to run for a short amount of time, even if the generators can not keep up. The energy storage is tiered as well, cheap but small batteries for early game are available as well as expensive energy banks with huge capacity for late game.

- **Mining Tools** are essentially upgrades to the speed and yield amount of mining operations on the world map. Four different options are available, pickaxe, pneumatic drill, tunnel bore and mining laser, each getting more complex and expensive in construction costs. When a mine is created to automatically produce ores, the type of equipment given to it influences the efficiency of the mine as well, therefore mining tools are not just a one time upgrade.

- **Storage Upgrades** in contrast to mining tools are just a one time advancement. Elements have to be stored in different conditions, as for this game, they are summarized to normal or unharmful; gas storage for any gaseous elements; airtight for toxic or highly reactive elements, to prevent them from either leaking or reacting to for example the humidity in the air; and finally radioactive storage, to shield from radiation.

  Before any of the relevant storage upgrades have been bought, only elements that classify as normal can be obtained. This system provides a minor hurdle, but also an advancement method to somewhat structure the progress.

All of these machines have to be "bought" or rather crafted, costing both money and materials. The material cost acts as a way to keep certain advanced machines from being obtained too early in the game, since rare materials need a lot of progression to be obtainable.

At the same time, every material cost was chosen carefully with a purpose in mind, even though there was no way to follow real life material lists for those kind of machines. Starting from the most common uses of elements, it had to make sense to add a specific element to the list of crafting materials. For example, neodymium is used to create the strongest magnets, and as such constructing the linear particle accelerator requires a big amount of it. Another example are nuclear reactors, using lots of lead and tungsten for shielding, tons of steel and concrete for general building materials, cadmium and boron as neutron absorbers, and beryllium as neutron source, among other things. While most material lists were guesswork, keeping it as realistic as possible with regards to common uses for elements was very important.

4.2.5 Production

The production page is for actually putting the blueprints in action. The player can add a new processing chain by choosing an already discovered blueprint, which will automatically build the framework of this chain. This framework requires the player to add the relevant machines, of which the player is free to choose their tier if not otherwise specified. The framework will also show inputs and outputs for each machine, if needed.

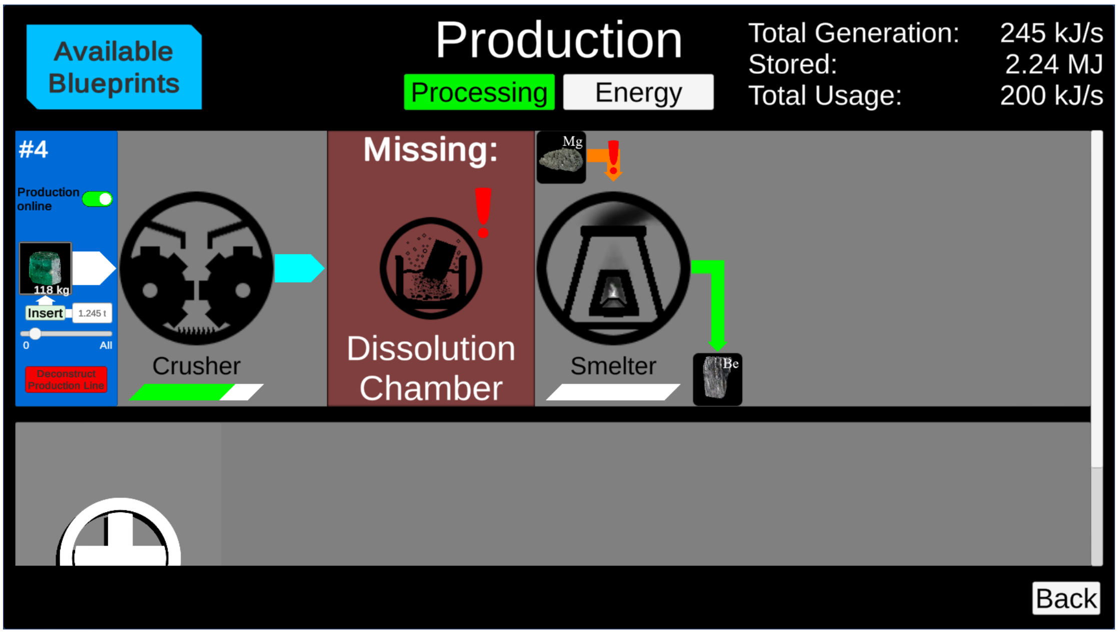

Figure 4.6: A screenshot of the overview page for processing chains

The most important input is the initial one, the main resource to be processed, in many cases an ore. This has to be set first, as every other ingredient is depending on the amount of the initial input, since inputs and outputs are handled in percentages of the initial resource amount.

Setting the amount to put into this processing chain, as well as a few other options, like setting the production online, is handled in a small control center in front of every production chain.

The production page also features an energy tab, where every owned energy generator can be seen. If necessary, fuels can be set here, and an overview of the current energy production, usage, and stored energy is shown, using joule as a unit of measurement.

4.2.6 Inventory

Finally, the inventory page displays every element, ore or resource and their amount currently in possession in a typical grid-like fashion, showing only icons and the amount. Hovering the mouse over any icon displays the name of the material in a tooltip.

Clicking on an item opens the option to sell an amount of this resource, which is the only option to actually earn money in the game. The prices should try to emulate the real world market to keep with the realism theme, and provide the player a feeling for rarities and prices of the elements and other chemicals.

4.2.7 Concluding Details

The main features are all included within these six main pages of the game, as the concept is relatively simple, and depth is created through the amount of content within the database.

In addition, the game features a saving and loading function, copying the game status into easily shareable text files. Especially since achieving the goal of collecting every element can be a lengthy process, this feature is important.

Artwork for the game consists of an icon for every element, ore and resource, as well as an illustration of each machine.

The relative simplicity of the game's user interface framework signifies the importance of the research that went into the database even more. Therefore it is consequential to provide the best possible environment for players to explore the very knowledge that constitutes the core of the game.

Why and how for this reason the development is not yet finished, will be discussed in the next chapter.

5 Evaluation

The evaluation of "Elementary" abnormally began during the development. The aim of the game and its conceptual status as a passive serious game demanded a distinct assessment of abstract values.

The findings of this informal self-evaluation will be examined in further detail.

5.1 General Problems

While developing the game, a few major problems became apparent within the game's core design. Those issues stagnated the implementation and led to features not being as effective as intended.

The following problems emerged alongside the implementation and are as such personal insights into the flaws of the concept of "Elementary".

5.1.1 Depiction of Production Lines

Processing chains for the production of elements and other resources are the core functionality of the game, they are the most important feature for progression, and the center of the knowledge this game is trying to impart as well.

And yet, the presentation as a series of machine cards with arrows and progress bars does not quite fulfill this role satisfyingly enough.

Even if the machines were presented as animated sprites to make it more vivid, the limited space and the flat, linear setting cause a disassociation, especially if many production chains are build and the page becomes just a long scrolling list. Long blueprints become horizontally scrolling strips within this list, and complex, non-linear production lines, like the one for platinum metals depicted in Figure 3.2, are even worse for the general comprehensibility since they have to be scrolled both vertically and horizontally within this list of processing chains.

Keeping these complex chains manageable and clearly laid out, once they exist in greater numbers, is a balky challenge and may be too complicated for a game just relying on user interface functionality.

5.1.2 Blueprints and Oversimplification

Loosely related to the previous point, the feature of blueprints of production chains bares another issue. While being first and foremost a game to the player, and only secondly a serious game trying to convey knowledge, the primary reason for the existence of "Elementary" is still for the players to explore and learn about the real world.

And while previously stated reasons for the simplification of real life complexity (See Section 3.2) still stand, it became apparent that the method of having the game do all the work of assembling the relevant processes creates a black-box effect. As soon as the game hand-holds the players as much as only having them click a few buttons, in this case set in the missing machines of which only the correct ones are available anyway, users stops paying attention to what they are actually doing in this moment.

This causes the learning effect to fade and can take away the motivation to explore. After all, the intrinsic motivation of learning about something because of the incentive to progress in the game is the core approach of this serious game.

With the blueprint system used, there is no real sense of accomplishment in working out how a resource is produced or seeing a chain of machines finally do exactly what was desired, while both of these achievements play a major role in the success of my personal experience of learning something in Minecraft mods (See Section 2.1).

A similar feeling might be gained from the eventual acquisition of an ore that was long missing, finally unlocking an element that is needed in many recipes, or similar experiences. To not denounce the entirety of the game, these moments can provide a learning effect as well, players might be likely to remember the locality of the ore or the importance of this finally obtained element in many processes, but the approach of presenting players with the entirety of a production chain in the click of a button, once unlocked, does not provide the necessary involvement and immersion to gain any knowledge from it.

The filling of missing machines and inputs becomes just a task, which is either done with a few more mindless clicks, or in case of some missing items, locks any progress in this direction and diverts the attention elsewhere, since nothing can be achieved for this part of the game at the moment.

5.1.3 Balance

Acknowledging the previous problem about blueprints brings up another grave issue: the balance of fun, realism, hand-holding, complexity, learning effect, motivation and immersion.

The reason behind the decision in favor of the blueprint system was to prevent players from having to piece together the often times quite complex chains of processes necessary to produce certain resources, the complexity of which is due to real life and dictated by nature.

Simplifying the processes further would diminish the learning effect, since the already obscure topics of the game are meant for the exploration of interested individuals in a playful environment.

From this perspective the question arises, if the complexity and amount of real processes even have a negative impact on fun. A person from the target group for this game would possibly feel motivated by the challenge of understanding and mastering the intricacies of elements, minerals and chemistry.

Keeping the contents as close to real life as possible adds to the immersion and provides a game environment of motivational loops. Playing the game with the desire to learn and explore is motivation enough to make the first advancements, understand the basic functionalities and achieve some discoveries. From there new prospects open up and should motivate players to keep on exploring and collecting, since every new advancement discloses new unfulfilled tasks and goals, just like the inspirational precursor Minecraft does on a smaller scale.

5.1.4 Amount of Content versus Amount of Gameplay Features

The scale of the content available in "Elementary" is effectively a problem as well. While it does not seem as deep from the beginning, a game in its last stages can be extremely cluttered and difficult to manage, as detailed in Section 5.1.1.

Since the amount of content is mostly due to the periodic table and the real world, and already just uses a selection of the most important resources besides the elements to make the processes function, this aspect is not subject to change.

The framework of the game's features however is constricting to the content and the player. The setting of the game within a two-dimensional user interface limits the amount of actions the player can perform, and there is an apparent danger of becoming stale and repetitive. The current form of the game requires the players to do essentially the same tasks for every resource, finding the source, discovering the blueprint, filling in the machines the blueprint needs, acquiring enough of the other ingredients and then producing it.

While a certain repetition is part of every game and defines its functionality and rules, in a user interface like this, these tasks can become tedious very quickly. To keep up motivation and immersion, the game needs to offer more than clicking the same buttons for every objective.

This problem is closely related to the issue within the blueprint system, as it fits every difference between all production chains, as diverse they may be, into the same process of actions.

5.2 Further Evaluation

Considering the problems arisen during the implementation, questioning the core concepts of "Elementary" was consequential. A few issues will be listed and discussed in the following. This includes the results of an informal evaluation and consultation with a small number of people, which mostly confirm the already stated problems.

- **Is the vague topic worth doing a serious game for?** The game centers around the idea of expanding certain resource gathering and crafting games to include everything on the periodic table and reproduce the processes of the real world. This particular approach has, according to research on related work, never been directly done for a game in this scale. Researching the production of the elements even showed that no consistent collection of defined information for this matter exists, a large number of sources was necessary to get the same level of detail for every element (See Section 3.1). This indicates either a general disinterest on the subject, or a complexity too high for attempting such a project.

  With only a few simplifications, the complexity of real life was turned into a compiled database ready for the game, and adjustments to up the realism even more can be done without too much trouble. Adding different or lesser used processes that have been left out is also possible within reason. Therefore the issue stems from another place.

  Arguing against the purpose of this knowledge is valid, but a serious game is not required to teach about school subjects or other applicable information. The key towards the topics of this game is motivation through own interest. A considerable example of this concept is myself being motivated enough to learn and compile the information about all the elements for this game from various sources and having fun doing so, even though there was not even a game element to it. The people asked about this project were also by the majority interested in the topics, or curious to explore in part at least.

  Concluding this question, it is possible to say that the topic is not too niche or too complex for a serious game, the correct target group can find a lot of motivation and fun within learning the intricacies of the production of elements.

- **How can motivation be created?** While it has already been established that the most important motivation has to come intrinsically from the players themselves and from their general interest and curiosity, the game has the task of stimulating it further and giving incentives to keep exploring.

In part the game in its current state already offers some incentives. The objective of collecting every element and completing the periodic table provides a clear end goal from the beginning, while sending the player on a quest with the impulse of completion. Further motivation is set by the seamless concatenation of resources. Many materials depend upon others for production, but there is always a starting point from which new options become unlocked. The possibilities cascade with every step, the game is always offering new paths to progress, which should pull the player in and motivate to keep going.

Another important way of creating motivation, which is lacking in "Elementary" in its current form, is immersion and involvement. The user interface-only approach is not providing a great sense of immersion, and the abstraction of processes to blueprints, which create a black box effect, takes away from the player's involvement.

Having the players feel accomplished by achieving tasks with their own work and own knowledge, instead of the click of a button from unlocked hand-holding mechanics in the game, can make a big positive difference in motivation to keep playing and learning.

The inclusion of players into the progression generates a personal relation to the achievements. To establish this level of immersion, the approach of a user interface game is not suitable enough, it creates a feeling of high level overseer control in front of abstract screens and numbers. A player actually building the machines and maintaining the productions from close up would be much more immersed, therefore understanding the processes on a higher level of detail. This allows for the players to see successes as personal achievements from detailed work and the gain of relevant knowledge, which can inspire to explore the new opportunities attained. From there, knowledge about the details of chemical processes is re-applicable and builds upon itself. As such the motivation to learn more is supported through relation and accomplishment.

- **Which level of detail is too complex?** Motivating the players through involvement on a low level with many details is a balance act. It is easy to lose oneself in the complexities of chemistry, which is why the concept of "Elementary" tried to abstract the details so much. Processes are combined in blueprints to a chain of machines with no view or care for the materials going between those machines, only the raw inputs and outputs matter. The order and connections of individual steps is irrelevant as well, as blueprints only show the completed chain in a fixed state.

  Leaving out those abstractions would mean to see every processing step as an individual recipe, one machine transforms a material with a certain amount of extra inputs into a specific other material. This requires for every intermediary item to be represented in the game as well, which would at least double the amount of items and possible processes.

From the player's perspective, these details would mean having to know how to produce each individual intermediary product to create the processing chain from ore to element from scratch. In some cases this is easily done, in others it proposes a complex challenge. Taking into consideration the previous discussion about motivation and immersion, succeeding such a task through intrinsic interest would be highly motivational and very informative at the same time. People playing this game might want to be challenged in such a manner to ascertain the intricacies of the topics they are interested in, and to experience mastering the elements by themselves.

For the correct target group, a higher level of detail should be manageable. If the game offers enough optional support through making it easy to look up how each chemical compound can be produced, then the complexity of real life should actually pose a motivating challenge instead of discouraging and confusing players. The approach of hand-holding and abstraction is not as well suited for these types of topics, complexity needs to be embraced in details to understand it and learn about it.

Ultimately, the game "Elementary" was approached from an angle which did not immediately show the issues within its concept. After the analysis of the aspects of the game and its content, as well as the conception of the player's motivation, the new insights can guide a new approach towards this game.

6 Future Work

After reviewing the game's problems, discussing player conceptions and concept ideas, an outline of the new approach towards the serious game "Elementary" will be presented for future work, as a solution to the evaluated issues.

6.1 Details instead of Abstraction

The analysis made clear how flawed the blueprint system approach was. Encapsulating entire processing chains into one entity makes it easy to abstain from modelling every intermediate product; only the order of machines, the input and output, and any further ingredients for the machines are important. This defeats the purpose of the game, because this abstraction does not incentivize the player to actually look into the details of the process and gain knowledge from it. Rather the opposite is the case, players are enticed to mentally discard the production chains and simply click through the necessary steps to obtain the elements.

The game should instead challenge the player by providing only the individual steps as building blocks. As an example, the player discovers the ore pyrolusite and learns the element manganese can be extracted from it. The game allows players to look up recipes, and as such shows that pyrolusite can be solubilized by treating it with sulphuric acid in a dissolution chamber, resulting in manganese(II) sulfate ($MnSO_4$). Looking up this compound will show manganese can be extracted from it by putting it into an electrolytic separator together with water. By building these two machines, and maybe connecting them to automatically turn the from pyrolusite produced $MnSO_4$ into pure manganese, the player can build their own production line.

The results and methods used are the same as in the current game concept, but putting the actual work into details should have a much greater learning effect, as well as rewarding the player with the feeling of personal achievement and in turn motivation.

The concept of keeping every process detached from one another needs a solid system to look up every recipe, because the game should not aim at making the players go to external sources for information about how to produce certain items. On top of that, connecting processing steps to build own processing chains needs to be simple and available for automation, in order to keep the player's work focused on setup of such processes, and not the maintenance and fueling of already established chains.

Means to automate machines, their connection and their filling with ingredients or fuel, pose another way of utilizing the obtained resources and tracking progress, providing another aspect of gameplay.

6.2 Immersion through Game World

Especially together with the previous change in features, immersion is more important than ever to keep motivation high and provide players with a rewarding feeling through accomplishment of own work. The distant way of controlling the game with just a user interface and numbers and symbols, is therefore not enough.

While the previous section detailed changes to the game's data and handling of its content, this issue concerns the visuals and gameplay itself.

The best way to immerse the players and bring them towards the low level would be to turn "Elementary" into a 3D game and set the player directly into the world. Machines would be physical objects to build and set up, ingredients need to be inserted by hand and so on.

While elongating the game progression, this method would also turn the project even more into a game. Controlling an avatar to do the construction and setup work by hand makes the experience so much more immersive and personal, adding towards the learning effect through actual experience.

Aspects of the game like mining operations all over the world or analysing certain resources could still be handled over interfaces, for example through screens in game showing the progress of external expeditions or scientists in the laboratory. The construction of processing chains and the collection of elements is the most important part of this new first person perspective.

The implementation of an actual 3D game world, to house the mentioned aspects of the game in, is a lot of work. Especially since the changes to certain features assimilate its inspiration anyway, the whole game could potentially be turned into a mod for Minecraft instead. Several functionalities of the new concept are already available in the game and function similarly to experiences with other mods.

To use this established platform to portray the core aspects of "Elementary" in a popular and familiar environment and utilize the research on the production of elements that way is a very broad idea and would need considerably more research.

6.3 Expansion towards more Variety and Realism

Finally, in an established game with both detailed processes and an immersive game world, the core content of "Elementary" could, and in some cases even would need to, be expanded. The collection of sources and processes for each element underwent a detailed selection, to only take the most common and easiest methods of production into the game.

Reversing this process to an extend and broadening the content of the game to include all industrial feasible production methods, a wider selection of ores, and more materials and machines would provide the player with a greater variety of options and consequentially also a better effigy of real life.

Whether there is a turning point, where options in the game become too overwhelming and too close to the complexity in the real world or not, is subject of another discussion entirely.

7 Conclusion

This thesis attended the conceptualisation of an idea about the passive learning effect from realistic game processes, its implementation into the game "Elementary" using the topic of producing the chemical elements as content, and a detailed evaluation of flaws within the concept as well as solutions for them.

Detailed insights into the experiences with Minecraft modifications explained how the idea for this game was inspired, a serious game that aims at imparting knowledge purely passively through the portrayal of real life correlations and features. Understanding how the game works and how to progress is simultaneously the learning of actual realistic knowledge.

Furthermore a few games about the topic of the periodic table have been reviewed, to reveal how focused on facts about the elements or the periodic table most of them are. Games about the extensive processes of obtaining elements from their sources are not available. On top of that, a real life example of element collectors shows another inspiration for the goal of the game "Elementary" and how incentivizing this hobby can be.

Since the content of the game is very extensive, a large database had to be compiled. For this, information about every element and their sources had been collected, the complexity of real life was reduced in part by formulating a specific process for each element and fitting each step to a set of machine operations. Together with accompanying details about elements and other resources, the game's database was compiled and formed the basis for the game.

Several features were implemented to complete the gameplay within this user interface based game. An interactive periodic table acts as a lexicon for information about elements, and at the same time as a progress tracker towards the goal of collecting each element. Ores and other materials are gathered from the world map, new information and new blueprints can be gained from the research laboratory, machines and energy generators are used in the production of elements and act as a way to utilize acquired resources. The concept of the game is based on a cascading unlocking of new options to progress, as elements depend on other resources to be processed.

After development stagnated heavily and a number of issues became apparent within the game's core features, these problems were analysed in detail, along with evaluating the game for conceptual values. The level of abstraction to avoid complexity in details was alienating players from the purpose of the game, and the user interface approach was deemed not suitable enough.

In discussing several key concepts, the aspects of motivation and immersion crystallised as centers of improvement. Around these values, finally a number of features were proposed to define the adapted concept on how to put this serious game into effect.

While the development of the game "Elementary" was in part misguided, the analysis of its flaws provided great insights into the necessary conception of a game with these proportions. The passiveness of knowledge from this serious game, together with the vagueness and complexity of the topic of chemical elements requires a great act of balancing, but with the necessary features and motivation, the game and its particular idea has great potential.

List of Figures

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