Turning The Nitrogen Cycle into an Augmented Reality Game

WORCESTER POLYTECHNIC INSTITUTE
LEHR UND KUNST
1865

BOYS & GIRLS CLUB
of Fitchburg and Leominster

Charles Anderson • Ethan Pollack • Hasan Gandor • Phillip Bui • Le Vien

Turning the Nitrogen Cycle into an Augmented Reality Game

An Interactive Qualifying project (IQP) submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the degree of Bachelor of Science/Arts

Submitted by:
Charles Anderson
Ethan Pollack
Hasan Gandor
Phillip Bui
Le Vien

Submission date:
December 16, 2022
Submitted to:

Worcester Polytechnic Institute
Professor Andrew Teixeira
The STEM Education Center of WPI

Boys and Girls Club of Fitchburg & Leominster
Allison Digirolamo
Kathy Chen

Acknowledgments

The IQP Nitrogen Cycle Game Development group would like to thank the following individuals and organizations. Without their guidance and support, this project would not have been possible:

- The Boys and Girls Club of Fitchburg & Leominster
- The STEM Education center
- Kathy Chen, Executive Director at STEM Education Center, for providing us with resources to complete the game.
- Allison Digirolamo, STEAM Director of The Boys and Girl Club of Fitchburg & Leominster, for giving us direction for our project.
- The students that volunteered to test and give feedback for our prototype game.
- Professor Andrew Teixeira, for giving us excellent group cohesion and constructive criticism.
- Worcester Polytechnic Institute, for giving us the chance to complete this project and game.

Authorship Table

Number	Section	Primary Author(s)	Primary Editor(s)
0	Abstract	CA	EP
1	Research	CA	EP
1.1	Background Introduction	CA	EP
1.2	Greater Issue Analysis	CA	EP
1.3	Nitrogen Cycle Introduction	CA	EP
1.4	Chemistry and Nitrogen Cycle at the Atomic and Molecular Level	CA	EP
1.5	Human Involvement in the Cycle	CA	EP
1.6	History of Fertilizer	CA	EP
1.7	On Modern Fertilizer	CA	EP
1.8	Ammonia Nitrate Silo Safety	CA	EP
1.9	On Septic Systems and Runoff	CA	EP
1.10	Brief About Nitrogen Cycle in the Ocean	CA	EP
2	Project	CA	EP
2.1	Set Objectives for Our Project	CA	EP
2.2	Experiments with Languages and Engines	CA	EP
2.3	Learning Process	CA	EP
2.4	Theory of Game Design	CA	EP
2.5	Design Process	CA	EP
2.5.1	Influences	CA	EP
2.5.2	Aesthetics, Narrative, and Styling	CA	EP
2.5.3	Ideal Product	CA	EP
2.5.4	Prototype Creation	CA	EP
2.5.5	Website Creation	CA	EP

2.5.6	Proposed Ruleset	CA	EP
2.5.7	Implementation of Prototype	CA	EP
2.5.8	Testing With Students	CA	EP
2.6.1	Instructions to Play	CA	EP
2.6.2	Survey	CA	EP
2.6.3	Analysis of Feedback	CA	EP
3	Conclusions	CA	EP
3.1	Analysis of Success	CA	EP
3.2	Analysis of Revisions	CA	EP
3.3	Greater Implications	CA	EP

Table of Contents

Table of Figures

Table of Tables

Abstract

The natural nitrogen cycle (NNC) is an important part of the world's overall ecosystem. It is integral to all life, especially human life. The nitrogen cycle is a process that can easily go out of balance through human development. Some of the ways humans unintentionally affect the natural nitrogen cycle is through the agriculture industry and waste disposal systems. The agriculture industry is the largest factor of human incursion in the nitrogen cycle. It has gotten to a point where there is arguably a man-made nitrogen cycle that exists within the agriculture industry. Both the natural and man-made cycle influence each other. Sustaining both the natural cycle and the artificial one is key if the agriculture industry expects it to be at equal or greater levels of production as to what it is currently. This environmental relationship can almost be thought of as a resource balancing game, or an optimization game. The word "game" used here is not meant to diminish the severity of such ecological systems but meant to embody the creation of an imaginary model which can give us differing outcomes based on input. In current culture, games are a common form of entertainment in today's world and one of the most ancient types of activity. However, with the advent of computers, games are now often said to have taken a new "dimension" of possibilities. This is embodied in the medium of video games and has been taken further with the recent technology of augmented reality (AR) and virtual reality (VR). Video games are a very recent medium with their origins going back to the 1950's with Tennis for Two, and only in the past couple decades where they considered to have their own merit as tools for education. Virtual reality, the ancestor of augmented reality, is also relatively new, having its modern iteration first shown in the 1960's with the Telesphere Mask. By combining the capabilities of AR/VR and video games, educators now have a wide range of possibilities for all sorts of education in a variety of fields. STEM education particularly due to the very hands-on and model driven nature of the subject. The goal of this project is to collaborate with educators and students to make an augmented reality game that aims to teach students about the nitrogen cycle and the greater social implications of human development in it.

1 Research

1.1 Background Information

The natural nitrogen cycle can be split up into two smaller but linked nitrogen cycles, the marine cycle, and the land cycle. This project is more concerned with the land cycle but does not attempt to exclude the marine cycle. The land nitrogen cycle greatly influenced how humans developed agricultural techniques. With incremental scientific developments towards fertilizers occurring throughout most of human history. Humans only started to greatly affect the nitrogen cycle adversely post the Industrial Revolution [1]. The agriculture industry is the largest belligerent of human involvement. However, the manufacturing, energy, waste disposal and septic industries are also key factors. Some of these factors have a more overt effect than others, but all affect the cycle in their own way and should be addressed. The game will attempt to address all these issues at least partially through its own means.

1.2 Greater Issue Analysis

The issue of human development with the natural nitrogen cycle revolves around our agricultural, manufacturing, energy, and waste industries being sustainable while trying to function to support the global population in the future. This is a difficult real-world challenge to solve as it is extremely multifaceted and is a grand-scale problem which encompasses several overlapping and diverse fields. These big problems are intertwined with larger problems which cannot be so easily separated out. So, it is necessary to create artificial divisions with these problems to make them easier to deal with. The reason why the nitrogen cycle matters so much from a pragmatic standpoint is that it directly affects food production and animal life. This is further compounded by the fact that nitrogen is a limiting resource that should be carefully balanced. Having too much or too little nitrogen circulating in the environment can have disastrous consequences on its own. There are many ways to tackle these smaller problems, but ultimately the effort will be to analyze every aspect of the problems at once and piece the solutions together like a puzzle. There is no single easy answer or solution.

1.3 Nitrogen Cycle Introduction

The land nitrogen cycle is reliant on the nitrogen in the Earth's atmosphere. The Earth's atmosphere is 78.08% nitrogen. But that is not mostly usable on its own. Nitrogen is part of the list for most common biological elements; Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, Sulfur (CHONPS) [2]. It can be commonly found in the formation of amino acids in DNA. Nitrogen is also a material of chlorophyll in leaves. Its presence in organisms is essential and it usually is not stationary in an organism [3]. The nitrogen cycle is composed of 4 basic steps: Fixation, Nitrification, Ammonification, Denitrification.

Fixation is when special bacteria in soil turn atmospheric nitrogen (N2) into nitrogen organisms can use. This process is very energy intensive. Ammonia (NH3) and nitrates (NO3) are usually the end products of this process. The creation of ammonia can also be done through lightning strikes as it breaks down atmospheric nitrogen and water. Lightning tends to create a small amount of ammonia naturally. Nitrogen in this form is relatively easy to already be uptaken by plants depending on the number of bacteria nearby. Certain plants like legumes have nodules on their roots which attract such bacteria. The species of bacteria in the soil which can fix nitrogen are nonsymbiotic. However, the bacteria which are symbiotic with the roots of plant legumes are of a different species. The health of a legume plant is very dependent on the productivity of its respective root bacteria [2].

Nitrification is the second step in this cycle. Once the ammonia is engineered by the bacteria and lightning. A different set of prokaryotic bacteria and archaea convert ammonia (NH3) into nitrite (NO2). These bacteria are commonly referred to as ammonia-oxidizing bacteria (AOB). Then another series of prokaryotic bacteria oxidize the ammonia and nitrite into nitrate (NO3). These bacteria are called "complete ammonia oxidizer" (comammox) bacteria. Conversion a slow process, but this results in the usable soil form of nitrogen. After this, plants can uptake the nitrogen in their roots. On a cellular level this process can be sped up with enzymes [2], [3].

Ammonification, the nitrogen left behind by the dead body of an organism is turned back into ammonium by decomposing bacteria and this nitrogen, in the form of nitrates, nitrites, and ammonia, return to the soil for use again. This could be considered its own miniature cycle. The more nitrogen input the faster this isolated cycle functions because the plant which uptakes grows faster as nitrogen is a major limiting resource. This is where the idea of some older fertilizer designs come from. Farmers would inset dead animals and manure into the soil where they were planting crops [2].

Denitrification, another specialized species of anaerobic bacteria convert nitrate to nitrogen gas (N2) and loose oxygen (O2). This effectively restores the same amount of nitrogen that was input as an output. Without this crucial step there would effectively be a limiting pool of nitrogen in the atmosphere that would gradually get smaller over time with no chance of natural growth. These bacteria make sure that such an equilibrium is maintained so that the environment does not deterministically destroy itself [2], [3].

There are more components to this process, but this paints a broad picture as to what processes are occurring. The finer points are going to have their significance touched upon when human development is discussed. Nitrogen could also be cited as a cause that would increase the consumption of other limiting nutrients in soil, like minerals. Fertilizer is usually never just pure ammonium nitrate (NH4NO3), it is usually also served with minerals that the crop needs to grow healthy. One of the situations where too much nitrogen has been injected in an environment is when plant growth is stunted due to an abundance of nitrogen but a lack of other minerals in the soil, such as potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), and sulfur (S) [4]. This situation is unique as it halts the plant's development at an abrupt phase. Plants that have consumed too much nitrogen show excess foliage growth. The soil the plant resides in may be super concentrated in mineral salts, which could lead to dehydration. Roots could grow stunted due to more energy spent into making foliage, which allows pathogens to infest the plant through the roots [5]. Both over intrusion of nitrogen and lack of it are harmful for the individual plant in different ways [2].

1.4 Chemistry and Nitrogen Cycle at the Atomic and Molecular level

Without discussing the nature of the intermediaries of the nitrogen cycle. The chemistry of the nitrogen cycle is as complicated depending on what processes the nitrogen undergoes. The cycle starts with atmospheric nitrogen (N2). Atmospheric nitrogen cannot be taken by plants directly and the compound must be broken. N2 is two nitrogen atoms bound together by a triple bond, which contains six electrons shared in pairs between the two atoms. Figure 1.1 demonstrates this type of bond. Triple bonds are covalent bonds that are far harder to break than a single bond, or a double bond. The breaking of an atomic triple bond requires a lot of energy and preferably a catalyst to speed up the process. Triple bonds are easily broken by lightning strikes. However, lightning strikes are naturally very infrequent. So, the next most energy intensive method would be for specialized bacteria to continually break down the bonds over time. Specific catalysts speed the breaking of specific bonds. The catalyst used in the commercial Haber process of ammonia (NH3) synthesis is iron (Fe) and is not consumed [6], [7]. For bacteria, this catalyst is not present. For ammonia (NH3) synthesis in a series of bacteria, atmospheric nitrogen (N2) is combined with other elements, such as hydrogen (H) and oxygen (O) [8]. Different types of bacteria convert nitrogen into its various usable forms. The most common usable forms for plants are ammonia (NH3), nitrates (NO3-), and nitrites (NO2-). These compounds will reside in the soil and will be absorbed by the plants to engineer their own amino acids and proteins [3]. Because all living organisms contain nitrogen as part of their composition, when they die, a specific set of decomposing bacteria will break down the materials in the corpse of the organism back into usable forms of nitrogen. Any excess of nitrates, ammonia, and nitrites will usually be processed by denitrifying bacteria back into atmospheric nitrogen gas (N2) and its leftover materials from the larger compounds. This cycle happens continuously and all steps in an ecosystem occur at the same time. Bacteria that reside in legume root nodes can convert atmospheric nitrogen directly into the plant for it to be usable. Figure 1.2 is a simplified representation of the dynamics of the cycle.

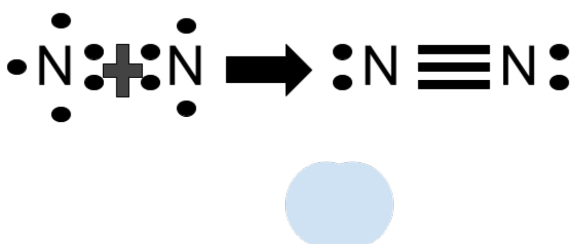

Figure 1.1 Atmospheric Nitrogen Triple Bond: Two nitrogen atoms combine to form atmospheric nitrogen with a triple covalent bond.

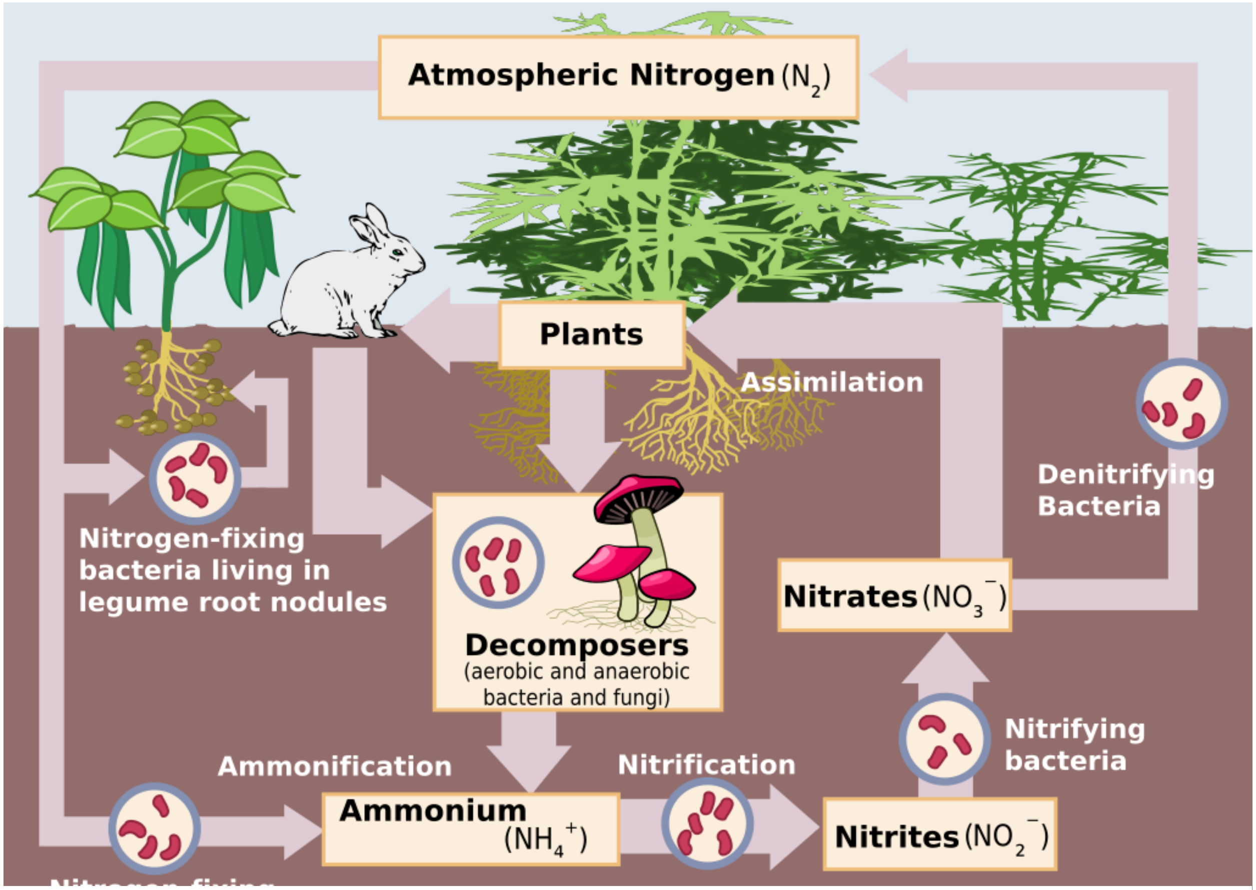

Figure 1.2 Simplified Nitrogen Cycle Diagram. Image Title and Credit: Nitrogen Cycle by Johann Dreo (CC BY-SA 3.0). This figure gives a simple model of the natural nitrogen cycle on land. Notice how some relations essentially function as their own smaller closed loop, like the loop between decomposers, ammonium, and plants. [25]

1.5 Human Involvement in the Cycle

Ever since the agricultural revolution, humans have had a lasting impact on the nitrogen cycle. Many faculties of human civilization like agriculture, manufacturing, transportation, and chemical engineering, affect the nitrogen cycle both directly and indirectly. Some of this involvement was intentional, but much of it was completely unintentional and destructive to the natural environment.

1.6 History of Fertilizer

The early use of fertilizer goes back to ancient times and appears in various civilizations like Rome, Egypt, pre-colonial America, and Mesopotamia. It was a common practice to use decomposing organisms to place in the soil around plants to bolster the harvest yield. These ancient peoples did not fully understand how this process worked. Different cultures had different implementations of fertilizer. Native American tribes used dead fish as fertilizer, while ancient Romans and Egyptians used various minerals and manure to fertilize crops [9]. These implementations largely revolved around just placing decomposing matter from another source in the soil near a plant they wanted to grow quickly. It was only until the enlightenment did scientists discover the importance of chemicals and nitrogen in fertilizer. The initial experiments for fertilizer were more centered around using varying combinations of minerals and testing which were the most important for different aspects of plant growth. Chemist Justus von Liebig argued that ammonia was the most important component of plant nutrition alongside smaller amounts of inorganic materials. From his research he developed an industrial method of treating lime phosphate in bone meal with sulfuric acid to make a kind of fertilizer. However, this design of fertilizer was not effective [8]. Knowing the importance of ammonia, farmers purchased and imported high amounts of guano, bird feces. Guano was considered an excellent fertilizer due to the high concentrations of nitrogen, phosphate, and potassium. Because the manufacturing of synthetic fertilizer was still extremely slow during the 19th and early 20th century, it was more economical, albeit not environmentally stable, for people to harvest guano from remote bird islands and South American countries. This would be the dominant way to obtain fertilizer until the Bosch-Haber process. It is also worth noting that minor wars were fought by major countries over the supply chain of South American guano [10].

1.7 On Modern Fertilizer

Most modern fertilizer is created through a variation of the original Bosch-Haber Process. This process is named after the German chemical scientist Fritz Haber. Haber had experimented with many different setups for efficient creation of synthetic ammonia, but only one was proven to be efficient enough for mass production. The Bosch-Haber process works by directly synthesizing ammonia from nitrogen in the air and hydrogen from very high pressures. The hydrogen used was obtained from natural gas in the form of methane. This process is still energy intensive; this is because Nitrogen gas (N_2) is inherently unreactive because of the atoms being held together by strong triple bonds. To keep down the energy input requirement, catalysts are needed, like increased pressure and iron [7]. The manufacturing of the ammonium nitrate itself does not affect the nitrogen cycle directly, but when the ammonium is implemented in a farm as fertilizer then it becomes part of the cycle. It is theorized that the reason why the global population exponentially increased in the middle of the 20th century was in contribution to the massive amounts of fertilizer being mass produced which helped grow an exponential amount of food [11]. It is unclear how sustainable such a manufacturing process is in the view of hundreds of years from now due to its heavy dependence on fossil fuels. All modern synthetic ammonium processes are derivations of the Bosch-Haber process. There has been attempts by scientists and engineers to cut down the standard supply chain dynamic that is required in older iterations of this process, in favor of a renewable, on-site production [12].

The ammonium nitrate produced in this process had a yield higher than predicted. Fritz Haber not only sought commercial success in the agricultural field with his discovery, but also found success in the military field with the manufacturing of explosives. This is because ammonium nitrate is a common material used to create propellant and explosives [13]. The explosive and reactive nature of ammonium nitrate causes some complications in storage. All explosive or energetic materials usually contain a variant of a nitrogen compound.

1.8 Ammonia Nitrate Silo Safety

While ammonium nitrate explosions are generally rare, they do happen with a great area of effect and are preventable with better safety measures. In 2020, the Beirut ammonium nitrate silo detonated and left a massive crater and claimed over 200 deaths as evidenced by figure 1.3. The total in property damage was around 15 billion USD. What caused the explosion was just simply a fire near the stores on a particularly dry and hot day [14]. Death tolls like this are not rare for an ammonium nitrate explosion. Due to how these silos store ammonium nitrate, usually in a very compact manner in mass, large detonations are extremely large. On a molecular level, ammonium nitrate is an effective explosive because it contains no carbon, only nitrogen and oxygen, meaning that it is made up entirely of gasses and because of this it is very sensitive to detonation by heat. When an ammonium nitrate molecule decomposes it results in 3.5 molecules of respective gasses. Agricultural silos tend to have a lot of air in them too, which lets fire occur and ammonium nitrate detonate [10]. A smarter utilization of silo space would be an effective prevention of such explosions. Hot and dry days are usually beyond human control, but what is most certainly preventable is workplace safety. Measures in the future should be taken to prevent such fires from happening. Some other notable explosions that were caused by fire are; Muscle Shoals, Alabama 1925 and Texas City disaster 1947 [15]. Some ammonia nitrate explosions were due to other human accidents; Roseburg Oregon 1959 and Tessenderlo 1942 disasters [16]. The circumstances that brought all these events about are quite similar. These were often preventable workplace accidents that involved misuse of combustible materials. While these explosions do happen infrequently, they are worth examining because they impact the lives of the human population that works with them and the environment which they live in.

Figure 1.3 Beirut Crater. Notice how the buildings were completely flattened and there is a near perfect circle where the silo was [25].

1.9 On Septic Systems and Runoff

Efficient organic waste and excrement disposal has been a project engineers have been trying to solve since ancient times. From the construction of outhouses to indoor plumbing, waste disposal has evolved greatly. The first "modern" septic system originates with a French engineer named Jean-Louis Mouras. As shown in figure 1.3, this rudimentary septic system design consisted of a concrete tank, which has an access hatch at the top, a wastewater input pipe, a fluid output pipe, an implicit filter which lets the hard excrement sink to the bottom. The waste at the bottom is usually layered on top of itself at different times due to how the tank is used. A septic tank must be large enough for serious retention of raw sewage and some decomposition for at least 48 hours. When a building gets its septic tank pumped, the hard waste at the bottom of the tank is what gets removed. From the fluid output pipe, the cleaner wastewater either goes directly to the larger sewer system or goes out to a groundwater source from an absorption field [17]. If it does go to a groundwater source, sometimes there is a complication where the connection to the groundwater source or the fluid output pipe does not direct correctly. This causes a surplus amount of nitrogen to carry over and dissipate into places it should not. Depending on where the septic tank is installed, this could manifest in many ways [17]. A common complication is that the excess nitrogen from the waste exits into bodies of surface water like the ocean, lakes, or ponds. Generally, the older the septic tank the more leakage it will produce. Older absorption fields tend to cause more runoff than newer ones. However, absorption fields that dissipate their fluid into the environment will always cause more runoff than just connecting the septic tank to the sewer system directly. In less densely populated suburban areas, it is not uncommon for septic tanks to just be designated to the plumbing of a single house. Due to the sparse spacing between houses in these areas, the absorption fields all tend to be isolated and have a greater area of coverage. This creates a situation where the nitrogen can easily runoff too far into water sources [17]. In places like Cape Cod or the Great Lakes, where houses are sparsely packed and each home typically has their own septic tank close to a body of water, it results in a lot of nitrogen runoff into these bodies. Because nitrogen is a limiting nutrient in bodies of water which contain algae, this could lead to an artificially stimulated strong

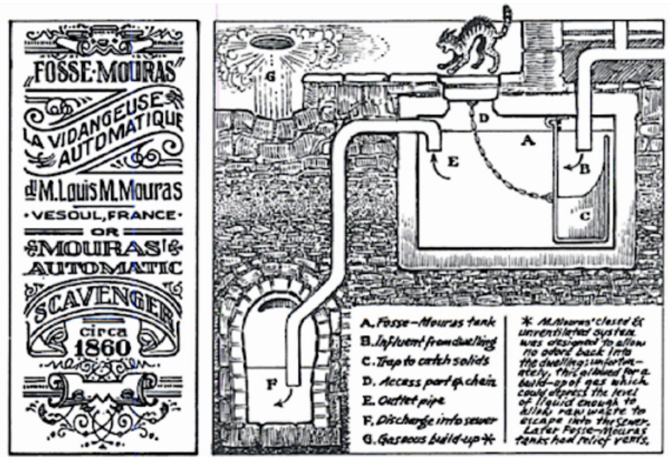

Figure 1.5 Fosse-Mouras Tank. An early diagram of a septic system designed by Louis Mouras [26].

Figure 1.4 An example of extreme algae bloom which can arise from nitrogen runoff from septic drainage fields. Image Title and Credit: Green algae on the surface of the lake [27]

bloom of algae in the body of water, as shown in Figure 1.4. This could lead to the water's other materials being depleted, particularly those in which animals require. Algae always consumes a small amount of oxygen and produces large amounts of it during the day because of photosynthesis [18]. Because photosynthesis requires other nutrients from its own water, this means there can be a situation where there is no photosynthesis occurring during a very large bloom and large amounts of oxygen in the water being consumed. This leads to organisms that depend on this level of oxygen, like fish, to become ill and die. The result of nitrogen runoff in a pond is extremely long algae bloom which depletes the oxygen at a rate where it cannot balance to replenish it. A solution to this problem would be to mitigate the absorption fields into some sort of sewer system instead of going back into the natural environment directly [18]. However, a feasible implementation has yet to be discovered.

1.10 Nitrogen Cycle in the Ocean

The marine nitrogen cycle (MNC) could be considered its own closed cycle. It is composed of several smaller cycles which have their own place in different layers of the ocean as shown in Figure 1.6. These cycles are contained in the Surface Ocean, Subsurface - Deep Ocean, and sediments. The crux of these cycles happens in the oxygen depleted zones (ODZs). This is because the ODZs typically house the highest concentration of nitrogen fixers and are in their own closed cycle. There is interplay and transfer of resources from one layer to the other. Aquatic ecosystems in general have their nitrogen cycle mirror the land nitrogen cycle with some deviation to the exact process [1]. The nitrogen fixers which convert the atmospheric nitrogen (N2) into ammonia (NH3) are cyanobacteria, but there are also non-cyanobacteria diazotrophs. The ammonia created by these fixers is usually not directly inserted back into the environment right away. Cyanobacteria are then consumed by certain species of phytoplankton when they secrete the ammonia into the water through excretion. In addition to this ammonia, urea (CO(NH2)2), another chemical also found in fertilizer is excreted. The absorption of these usable nutrients mainly manifests itself mostly in chains of other microorganisms, contributing up to larger organisms [19]. These larger organisms also contribute to nitrification by secreting waste and dying. For denitrification, many different types of bacteria will remove various nitrogen compounds, converting their input into N2 and some other waste products. From there the cycle feeds back into itself again.

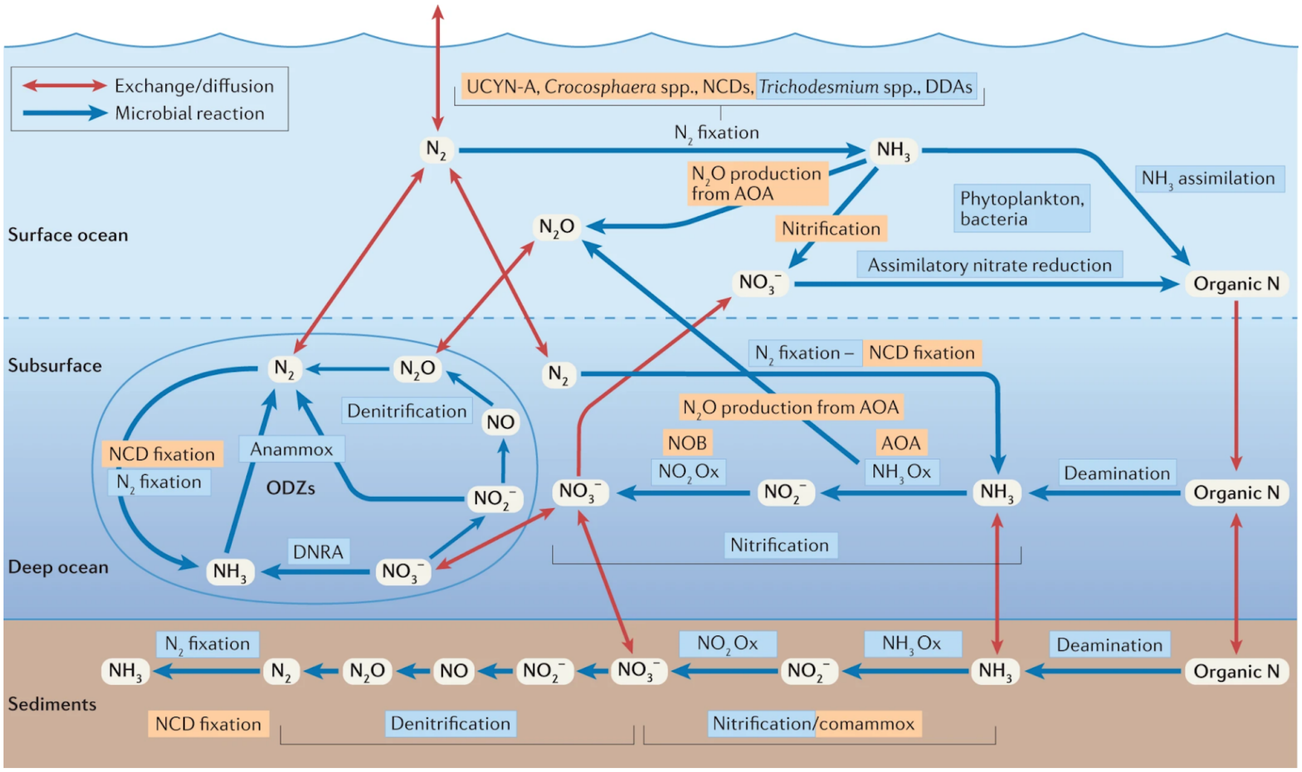

Figure 1.6 *The marine nitrogen cycle. Notice the enclosed loop at the ODZ and transfer between the layers of the ocean*[1].

1.11 Societal Implications

Shifting our perspective away from the nitrogen cycle, how exactly has the nitrogen cycle and the recent advancement of fertilizer impacted the human population? In a global scale, wars have been fought over guano deposits in South America up until the advent of the Bosh-Haber process. With the Bosch-Haber process brought about very efficient and streamlined methods for not only making fertilizer, but also explosive compounds which would provide technological enhancements for weapons. The widespread availability of these compounds would then go on to influence the design of firearm cartridges, bombs, mines, artillery shells and much more. It is unknown how much military technology would have fallen behind the current progression if it was not for the Bosch-Haber process. It is also theorized that the Bosch-Haber process indirectly contributed to the number of deaths in World War 1 and World War 2 that were brought about [13]. Not having the process be discovered could have saved some lives. At the same time, food availability has also been greatly increased. One of the consequences of this is the exponential increase in global population growth. At the start of the 20th century, a little under 2 billion people were alive. By the end of the century, this number quadrupled to around 7.7 billion as shown in Figure 1.9 [11]. If you compare this trend to the fertilizer consumption rate in Figure 1.7, you will notice that there seems to be a correlation with how much fertilizer is being consumed to how many people are in existence [11]. In Figure 1.8

it is also worth noting that the type of nutrient production in fertilizer starts off as having more equal proportions of potassium, phosphate, and nitrogen. Over time, more nitrogen keeps getting produced disproportionately to the two other nutrients. At the end of 2019, there then begins to be 3 times as much nitrogen as there is Potassium or Phosphate.

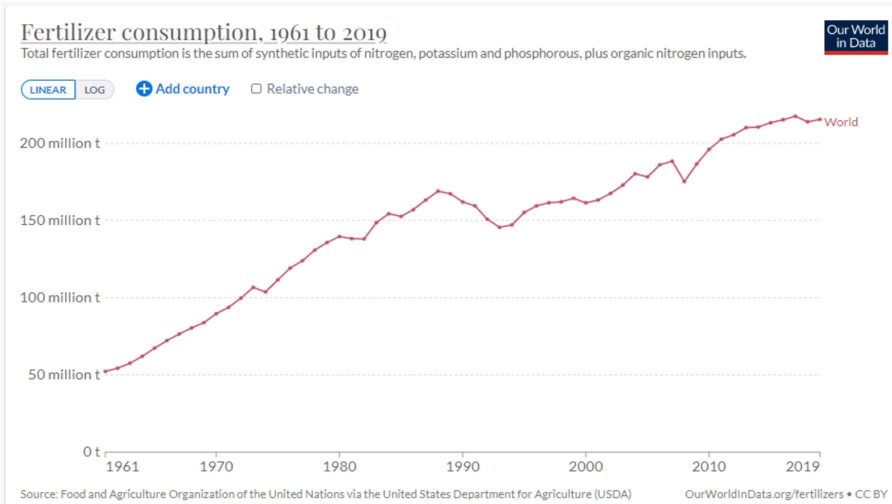

Figure 1.8 Fertilizer Consumption. Shows in tons, the amount of fertilizer consumption between 1961 and 2019. Notice how it is mostly a linear trend with a dip and slowly asymptote horizontally. This might account for the population leveling off [11].

This implies that not only is more fertilizer being consumed now than ever before, specifically it is the nitrogen nutrient that is increasingly becoming more consumed over the other nutrients. Because the traditional mode of producing fertilizer is through isolated factories and then shipping it off to large farming complexes or retailers, this makes the industry become reliant on the transportation industry. The transportation industry is one of the largest producers of CO2 emissions. One of the factors that lead to the increasing size of the ODZs in the ocean are the CO2 emissions [1]. To de-link the transportation industry and the fertilizer industry, there would have to be a shift as to where ammonia production and storage takes place. Preferably, this would mean a transition for ammonia production and storage to be closer to the same area as where farms that rely on large quantities of fertilizer are located [20]. This would in turn shrink the involvement within the transportation industry. It could also allow farmers to directly control ammonia production or be more involved

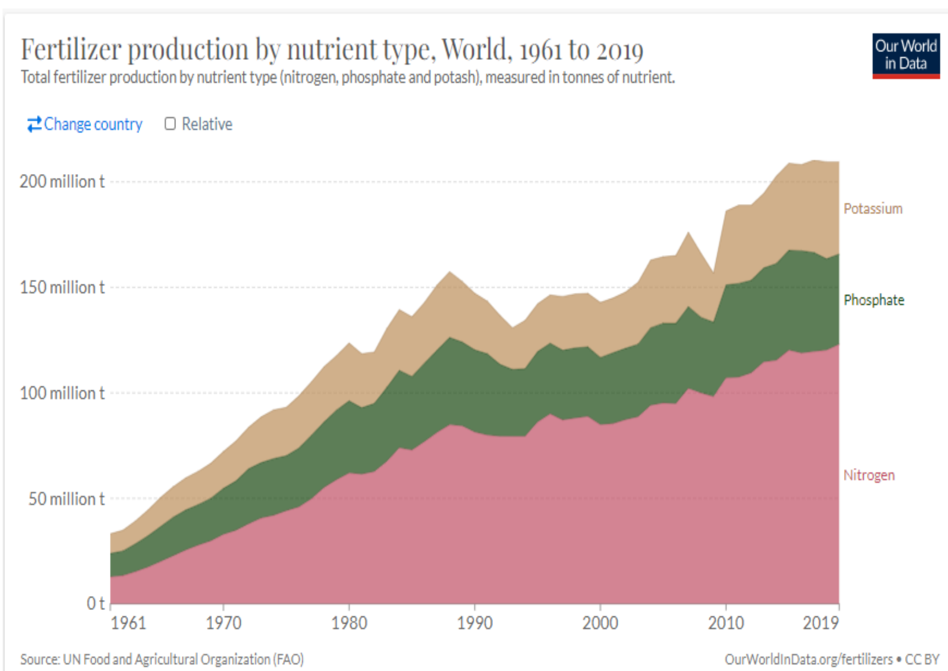

Figure 1.7 Fertilizer Production by Nutrient Type. Shows the amount of potassium, phosphate, and nitrogen production in relation to each other. While potassium and phosphate produced proportional to each other. The demand for nitrogen has linearly increased by almo

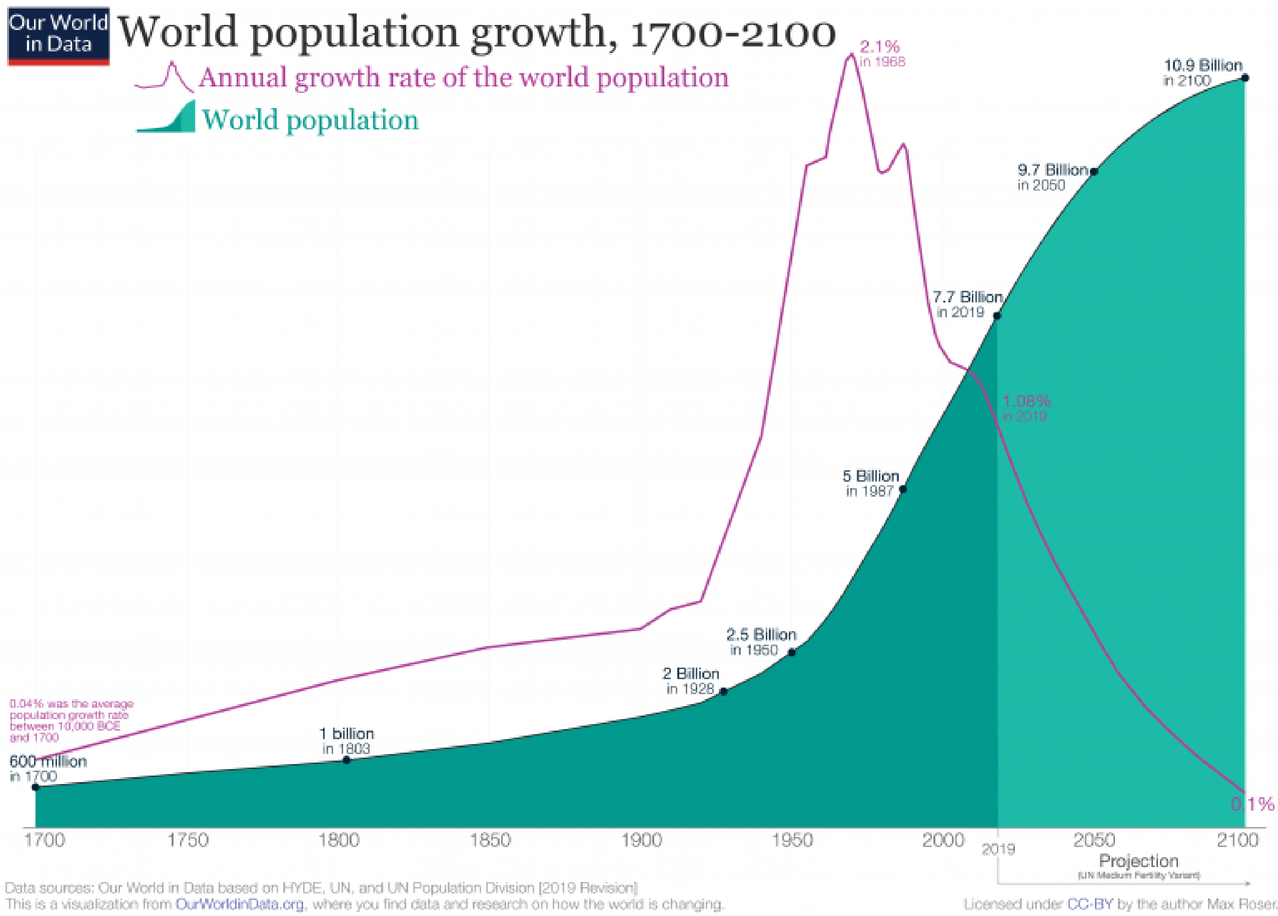

Figure 1.9 *World population growth. 1900 to 2000 is where you see the global population quadrupling* [11].

in the engineering process. This could effectively lead to a decentralized model of farming and fertilizer production. Local fertilizer production might cause a shift in equity between large industrial farms and local farms, possibly favoring the latter. While there is no major widespread effort for implementation of this solution, it is worth considering.

If the agricultural industry can't sustain itself at its current production level, there would be a horizontal asymptote in food production. This would most likely lead to a layoff in population growth. It is also important to note what exactly all this excess nitrogen that is being used is doing to the environment. Particularly how it will affect groundwater sources and large bodies of water. Traditionally, farms were built close to bodies of freshwater to easily create irrigation systems. With the advent of modern plumbing modern farms do not have to be built as close to groundwater sources as they used to be. However, like septic tanks, excess nitrogen from fertilizer in farms can seep into groundwater or other large bodies of water and contaminate them. This is especially dangerous if a drinking water source like a residential well is contaminated [21]. If these smaller reservoirs are contaminated this could cause a population to become very ill very quickly. It is an imperative that a solution that provides the integrity of drinking water exists alongside the development of fertilizer.

These are not the only societal impacts of the nitrogen cycle, but these are just some of the most immediate consequences of it. There will most likely be changes made to these industries.

2 Project

2.1 Set Objectives for our Project

Our IQP pertains to the environmental issue of maintaining the nitrogen cycle. However, the next step was to take this research and construct an augmented reality game from it. This game's teleological goal is to teach middle-school age students about the nitrogen cycle. The game is not meant to act as a crutch, or a replacement for an existing STEM curriculum, but rather enhance it as a supplementary resource. We examined common US middle school STEM curriculums to understand how information was being taught and what was valuable to teach [22]. Because the nitrogen cycle's natural processes cross over the fields of physics, chemistry, ecology, and biology, it was best to plan to include elements from all fields. Within the game's larger goal, there would be these smaller goals of trying to teach key points about science and its social impact. In general, these are the learning objectives the students should learn after playing the game to completion.

1. The nitrogen cycle is a fundamental part of our natural environment and needs to be cared for.
2. There are measures humans can take to prevent fast-acting disasters like silo explosions.
3. Because the world has a population of humans that need to regularly eat to function. Food production cannot be ignored for the sake of remedying the environment itself. The solution to the problem should not be to just cut off food or fertilizer production, but rather to find a solution that allows us to sustain production and keep the environment healthy.
4. There can be an equilibrium to a healthy cycle between the natural processes and human development.
5. The environmental problems will not cease because of lack of human development, rather this requires a solution which requires some direct human intervention in the environment.

These are not the only concepts the students should learn. These are more broader themes relating to the social awareness of the cycle. In addition to this, students will also learn about the specific scientific aspects of the cycle, aside from the social implications. There will be features in the game that will be designed for exemplifying individual topics. This includes topics like, nitrogen fixation, ammonification, nitrification, natural and artificial denitrification, Bosch Haber process, storage of ammonium nitrate, nitrifying bacteria and archaea, runoff, and how industry relates to pollution.

A prompt that was given to us by our IQP was the attempt to utilize augmented reality technology. Because implementations of augmented reality vary wildly, this objective was open ended. Augmented reality could be something like Google Glasses for working, or a game like Pokémon GO. The group deduced that middle school students are most likely not going to have expensive headsets, but it is not uncommon for middle schoolers in the US to have smartphones. So, utilizing the camera on a smartphone for AR purposes seemed to be the natural conclusion. The project advisor was pushing use of the HoloLens headset for this project, but the group deemed it unsuitable for its objectives. Most of the group members were doing their project credits 3/3 in C term, while only two members of the group were taking credits in B term of 2022. In B term it was decided that most of the planning, the experimentation, documentation, and the design would be done. The group held meetings with the STEM Education Center and the Boys and Girls Club of Fitchburg and Leominster to consult about the material in the game as well as gain access to a group of testers for feedback. These testers were middle school students from the Boys and Girls Club of Fitchburg and Leominster. These meetings were held to ensure that the project was achieving its objectives it set out for itself.

2.2 Experiments with Languages and Engines

The group examined multiple engines, application programming interfaces (APIs), scripting languages, and programming languages. A powerful contender was Unity game engine used in combination with C# language. This was largely due to the accessibility of the documentation and the interface, but after some examination, this idea was dropped because having an installation for a game was considered a messy experience and is not great for a younger audience to autonomously do. Unity is also a very hefty game engine tailored towards complicated 3D games and only had AR support as a secondary capability. Unreal 4 Engine used in combination with C++ was too resource intensive due to the engine being designed for games that required photorealistic graphics. We were considering using HoloLens 2 headset hardware in combination with Microsoft Dynamics 365 Guides as it was provided to us by WPI. The group decided not to use this because we did not have a lot of HoloLens headsets and development could not be distributed among the group members as evenly. Microsoft Dynamics 365 Guides did not have the level of inbuilt capability for the project's scope. Dynamics 365 Guides is a very simple scripting interface which can only be used to effectively make tutorial prompts for tasks in real life. It does not have the capabilities to make a complicated game in. Because we did want to avoid the liability of the user installing software on their devices, it was decided that a web-based language for a web-browser application. Our team had members which were used to working with JavaScript and many libraries, so it seemed natural that we would choose JavaScript, along with some HTML and CSS for our project. Our game will be accessible from its own website. The JavaScript libraries that were proposed to be used were ReactJS, Three.JS, and AR.JS as they are reputable and should have enough functionality to cover all our needs. We might need to use more libraries in tandem, but these three will be the ones we use the most.

2.3 Learning Process (of Game Development)

Some members of the group liked to play video games when they were younger and some of us still do like playing video games. Certain members had game development as a hobby. The group intuitively had a feeling for game design. However, we needed to re-familiarize ourselves with the JavaScript language and HTML/CSS. Each member worked on their own skills individually. There was a shared Google Drive among the group members where they could propose ideas to be implemented and view other people's ideas. Some ideas proposed included a scavenger hunt in AR, an interactive novel, a chemical combinations game. However, the idea that stuck was a City-Builder. This appealed to us because it was relatively intuitive and conducive to the idea of the IQP. A GitHub repository was created to keep centralized track of the development of the web app. Users could create their own version of the GitHub and submit their own code for staging at any time. This provided a relatively streamlined workflow. The group held internal meetings frequently to decide on what elements seemed fun, feasible and viable.

2.4 Theory of Game Design (Good vs. Bad Design)

Inherently, the end goal of all games as a game is simply to be fun. However, it is rare that a game usually exists to just be a game to serve its own ends. It is common for games, like other types of art or entertainment, to be used for a greater purpose outside itself. Here we are using games to not only provide a fun and entertaining experience, but as a teaching tool to connect with an audience in a creative way.

Because there is a history and a lineage of games and game design, it is common to build off instantiations of already existing ideas or tropes. Our culture tends to look at games in terms of "archetypes", or genres. Genres are mainly used as a marketing tool to separate out and promote games with similar conventions. Genres can tend to have subgenres, which are an even more specific group of traits from within. Popular genres to be played are sandbox, platformer, real time strategy (RTS), city-builder (CB), and role-playing (RPG). Most games fall into one or more of these genres. To the end-user, genres are effectively ways of classifying what to expect from a game's conventions. Different players have different preferences for what conventions they enjoy, but there is a science and an art to game design, so there exists a bad implementation of conventions, tropes, mechanics, and elements as well as a good implementation.

Games are often divided into an artistic aspect, a mechanical aspect, and a technical aspect. Artistic aspects relate to the aesthetic of a game, mechanical aspects relate to how a game is played, and technical aspects relate to how a game is meant to operate on its own hardware. Each of these aspects combine to create one holistic experience. Often, these aspects influence each other during the design process. Examples of artistic aspects are presentation, music, graphics, art style, design, story, and narrative. Examples of mechanical aspect are puzzles, resource systems, controls, levels, and interactivity. Examples of technical aspects are algorithms, optimizations, code, engines, libraries, hardware capabilities, and documentation. The instantiation of these aspects effectively flows from the goal of the game. Ideally your player should never directly have to interact with the technical aspect of the game on its own. However, your player will ideally always be interacting with the art and the mechanics. For the sake of simplicity, a good game is one in which all these aspects co-operate and sustain each other to create one consistent experience, and a bad game is one that is effectively damaged by its own aspects, creating an experience that is inconsistent. This metric allows us to separate a game's objective quality from the player's subjective preferences for entertainment, gameplay, and aesthetics [23]. This is not to completely disregard the player's preferences for entertainment, but rather to be able quickly work with it.

For our purposes, we will be using the faculties and aspects of games to teach kids about the nitrogen cycle and human development. The better the quality the game, the better the material will be taught to them. Games of poor quality tend to be forgotten by their players shortly after they are played.

2.5 Design Process

One of the first questions the group asked itself was "what game could emulate the feeling and the social implications around the nitrogen cycle?" The group acknowledged that the implementation of such an idea had to be intuitive for the player. An audience of young students would be the end-consumer of this game. The group also expected the game to not be replayed habitually. This meant that the game had to make very good first impressions and be understood by the player quickly. The game would also require frequent interaction with objects in the world so it would require a feasible interface. As this game would essentially be a city builder, an emphasis on the player planning for what structures they are going to place down. To assist this idea, the game would be played at a relatively slow pace for several reasons; the player will need time to safely experiment around mechanics, give time for the environment to just run on its own, to emulate real world environmental changes happening over long periods of time. Games are usually emulations, not simulations, which means that creative liberties should be taken to represent the essence of something in such a way that makes sense in the player's mind outside the game. It was generally accepted among the group that stretching the scaling of objects relative to the player's perspective was a good choice. The game did not need to be realistic in the way it handles quantities of resources, just educational in how it portrays these resources. The environment the player is affecting should have a series of "overhead" global statistics the game itself always knows. This is effectively the "game state", which will be an important piece of implementation and will make designing the rest of the game a lot easier. Not all the information known in the game state will be known to the player. In most strategy games, there is a generic unit class which all other units in the game extend from. Here, we decided to come up with a "node" system. A node is an enclosed structured unit of information which impacts the game world. It could be thought up as being equivalent to a "unit" in a strategy game. These nodes will be placeable by the player when they are brought into existence. Used in tandem with the AR capabilities of the user's device, nodes could be scanned into the game by real world QR codes. The QR codes provide a base for the node. QR codes were chosen because they are printable, easy to handle and easy to rearrange. The player interacts with these nodes to accomplish a series of goals deliberately structured in a progression system. This progression system should reward the player for keeping the environment in balance while also implicitly pacing the game. These three structures, the "game state", "nodes", and "progression system". Would be the technical cornerstones of the game's mechanics, and every other minor subsequent design choice would be implemented with these in mind.

The game is meant to be played with students as the main players, and parents or teachers as a mediator for some systems in the game. Because the QR codes are physical pieces of paper, they must be handed out to the students by the teacher. The game would still be perfectly functional if one were to play it solitary. However, it was designed in such a way where there would be a mediator, or referee, that was playing with students to keep the pace of the game.

Minigames were a debated topic because they were considered by some group members to be non-essential to the game loop. However, minigames could be used not only as a means of pacing the game, but to exemplify more specific aspects about the nitrogen cycle. A minigame could be themed after the breaking of the triple bonds of atmospheric nitrogen, or the formation of ammonia nitrate from inside bacteria. The possibilities are quite fluid.

Tutorials and tips would be an easy feature to implement as it usually just is a display of text as an instruction. They can also be of great assistance to new players. The in-game tutorials should just teach you the absolute basics on how to play the game and then let the player work with the rules autonomously.

2.5.1 Influences

One of the references we looked at when creating our "soft ruleset" was Spore (2008). The game's interface and gameplay as well as theme was very exemplary. It inspired our project to be a city builder within an environment that could be sculpted by the player. The environment the player interacted with was a planet with an overhead of conditions that could be modified. The player could build structures, place creatures, and take resources from the land. It was also a good example of a game where you had to carefully keep the resources in the environment in an equilibrium. Spore's drag and drop interface was relatively simple and it was also a game targeted to a younger audience.

An influence for the AR-dependent aspect of the game comes from Pokémon Go (2016). It was referenced primarily for being a very financially successful AR game in time period where AR was just beginning to become widespread. Pokémon GO continues to be played and had long term support. The game also had an elaborate map system that kept track of entities in the real world. While Pokémon GO utilized AR technology in a way different than we proposed. It was still useful as a reference. Pokémon GO also featured minigames, which allows the player to influence other aspects of the game if they complete them. These minigames were only about a few seconds long and never felt like they interrupted the main game.

2.5.2 Aesthetics, Narrative, and Styling

The original plan for aesthetics would be to take after similar educational entertainment games and simple simulations. Skeuomorphism in the heads-up display (HUD) and user interfaces (UI) is something generally discouraged in educational games as they draw the user's eye to the wrong focal points on the screen. This is not preferable for user interfaces in games in which the user is meant to have a relatively short experience with. The artistic direction the group plans to apply to the HUD would be minimalism. The amount of HUD and UI on screen simultaneously was preferred to be kept to a minimum.

To appeal to a young audience of middle school students, we decided to set the game's color palette that would remind them of science. Typically, STEM textbooks, educational websites, and simulations are given a color palette deliberately chosen to remind the user that they are on an academic service and are there to learn. A white or beige background scheme combined with bright green highlights for elements the player is supposed to interact with and light blue highlights for passive pieces of UI. White and beige were chosen as background colors because they allow other colors to stand out in front of them. Green inherently will draw the eye which will be useful for objects the player will be forced to quickly look and interact with. Blue passively highlights sections of the screen which makes it great for counters. This should also create a subtle association within the player's mind of what a piece of HUD does without even interacting with it.

For objects that are supposed to exist "in the world", designs reflecting real world objects will be given to them although their form would be simplified with an art 3D style. The concepts and models have not been designed yet. The plan is to have all artistic work completed in C term.

Sound design will have its resources be taken through free and open-source sound libraries. In B term, no sound design has been applied. The sounds will mostly be chosen for player communication and audible feedback for doing specific actions. In C term, the goal is to apply the sound design to the game.

2.5.3 Ideal Product

By the end of C term 2023, the group would ideally have the game, its art, website and mechanics all completed, and tested for quality. The game should be playable from the browser on a device with a camera. The game would be hosted on a web server and would be created in JavaScript, ReactJS, ThreeJS, and AR.JS. A website will be created to house the game so that anyone can access and play it at any time. This would also make updating the game very easy as there would be nothing to install on the end of the user. The game will be a "city builder" with a semi-autonomous world and a level of interaction through placing down structures. Although the player will be building a farm instead of a city. The player in the game attempts to reach objectives by producing the in-game resource of "Food", while trying to balance out their production with care for the natural environment. The player should be able to play at their own pace and not be afraid to use the Inspect Mode to take some time in learning about the exact science of the cycle. There will be minigames themed after certain chemical aspects of the nitrogen cycle to not only keep the player busy in the short term, but to teach them the science dietetically. There will be in-game objectives and tasks the player can fulfill for rewards. These tasks can be anything from placing down nodes, to inspecting elements, to acquiring a certain amount of Food. The goal is to combine both education and entertainment into a cohesive experience, rather than isolating them and serving them separately. The metric of success for the game would be how much the players learn about the nitrogen cycle from the game. We plan on collecting feedback and player information on that metric from surveys that will be sent out after playing the game.

The AR side of the game will be implemented in the form of QR codes which can be freely moved around. QR codes are going to be the anchor for the game's nodes or contained units of information. These nodes will contribute to the overall statistics of the environment. The nodes will usually have a 3D model rendered on top of them in AR, specific to that QR code. The same QR codes can be shared by different players. Each player is supposed to keep track of their own environment. This gives the game's environment some material feels. Because the player is using a device with a camera, it will be easy to overlay minigames onto the screen and to quickly switch back to normal gameplay. A minigame will relate to another mechanic and will try to exemplify a specific part about the science of the nitrogen cycle. For example, there could be a minigame based on breaking the covalent triple bond of an atmospheric nitrogen compound. This could be done for a reward in game. The standard processes of the game will continue while the user is distracted by the minigame. The transitions between the standard gameplay and the minigame should be almost seamless.

The game's colorful but simple HUD and UI should help guide the player's eyes to visual elements as they need to be presented. A color-coded scheme will be preferable because it's a way to understand what certain pieces of UI do before they even interact with it.

The aspects of the game's implementation in AR will have to be up to the IQP group in C Term as that is the term where the most effort will be spent. In B term, a proof-of-concept prototype was made in order to encapsulate many aspects of the AR product.

To encapsulate how this finalized gameplay loop should feel without being too convoluted. It would be best to imagine how the finalized game should play from the perspective of the player in the middle of the game:

Our player, Billy, is using his phone to scan in QR codes which correspond to nodes. He has several nodes of different types placed down on the field. He is in a classroom and is playing the game with 4 other students and there is a teacher monitoring the activity. Billy is trying to get to the next achievement, which asks him to inspect a group of cyanobacteria in a pond. In inspect mode, Billy points his phone to the QR code for cyanobacteria and clicks on the 3D model appearing on his screen. Billy reads a small block of text that explains what the purpose of the cyanobacteria is and how they work. After reading through the lesson thoroughly Billy is awarded 50 foods. Billy gets a notification when he moves his camera over one of his plants saying that he must help to break some triple bonds of atmospheric nitrogen. He taps on the prompt that appeared on the node, and then his phone camera overlays a second screen where it prompts him to play a minigame where you must break atmospheric nitrogen bonds as quickly as you can for 10 seconds. After the game is over, Billy sees he is rewarded food relative to his performance in the minigame. Billy then sees that the nitrogen runoff content is at 6, which is high, so he decides to spend food to scan in a denitrifier. Billy asks the teacher if she can hand him a QR code for a denitrifier. The teacher asks Billy why he needs one and Billy gives an answer touching upon why high nitrogen runoff is bad for the environment. Billy answers correctly so the teacher lets him scan in the QR code. The newly placed denitrifier is at level 1, but he has enough food to upgrade it to level 2. This decreases the runoff in the environment from 6 to 4. Slowly, Billy notices the pond node has less algae in its bloom.

This player-perspective description tries to encapsulate the player's thought process moment to moment. Ultimately this is the dynamic the game will seek to replicate. It combines strategy, science, social interaction, and a sense of progression to bring together a cohesive experience.

2.5.4 Prototype Creation

In B term 2022, to make sure our game systems and ruleset made sense. The group facilitated the creation of a prototype game. A simplified version of the game converted not to use the AR technology we proposed. Following our proposed ruleset, we decided to create a simple web-based prototype that is played on the same website that the AR game was supposed to be played on. Creating the ruleset was a large part of development time as the game contained many systems working simultaneously. Instead of using QR codes to place nodes in the real world, this version would utilize a map in which the player drags and drops nodes onto the map to put them in play. The game system keeps track of what nodes are in play and what nodes are not. The game is played on any device, but it functions best on a PC with a keyboard and mouse. In these areas, that is where the prototype substantially deviates the most from the final version. The game can only run in a chromium-based browser due to its utilization of JavaScript. The prototype will be used in the future as a mock-up reference for the AR game that will be created in C term.

2.5.5 Website Creation

The website will be written in a combination of HTML, CSS, and ReactJS. The website does not have a domain yet and only runs on the server's localhost The main pages of the website are:

- Home (Index): This is the page the URL automatically redirects to. It is functionally the home page where all other pages are accessed from. Its like a hub for our project. There will be a navigation bar where the pages are indexed from.
- Science of the Nitrogen Cycle: This page will contain a straightforward overview of the science of the nitrogen cycle and how human development affects it. It will be presented as an article.
- Downloads: This page will contain links and materials to download and print the QR codes as well as instructions for teachers on how to run the game with students. This portion of the site will not be restricted, and this makes all the external resources of the game effectively free.
- Resources for Teachers and Parents: This portion of the site will contain an educator-oriented analysis of the game and a disclosing of the game's content and subject matter.
- About Us: This page explains the game's purpose, contains information about the people who developed it. It should also contain links to the group's personal websites and portfolios.
- Credits: This is a page filled with basic credits and team roles.
- Game Page: This page is where the site will prompt the client to run the browser game.

Figure 2.1 *Index. Current homepage for our website.*

2.5.6 Proposed Ruleset Storyboard

The written rule set that was devised for the digital prototype is written here. This is an abstract set of rules which govern the game aside from any specific implementation:

Terminology: This game uses words with specific definitions with different meanings than their counterparts:

- Player: This is a basic participant in the game who is trying to balance out the nitrogen cycle. In the real world this would usually be a student. A player requires a device with a web browser to play the game.
- Mediator: This is usually a teacher or a person who can administer the game externally. The mediator's job is to guide players along the game and to give players QR codes for doing certain tasks in-game. The mediator does not need their own device to participate in the game. The mediator's role is equivalent to a referee in a real-world sports game.
- In-Game Environment: Also called "environment", but it's the virtual representation of the real-world ecosystem which is supposed to be represented by what nodes and overhead data are at play.
- Node: Player or System based unit of information, usually anchored to a QR code, that affects the game state in some way. In the prototype they are enclosed units that are dragged and dropped onto the map. The effects of nodes stack on top of each other. Nodes cannot physically overlap each other when placed on a map. Each QR code will be labeled to its node type. All nodes have a horizontal placement radius measured in centimeters specific to that node type that is visible to the player. All nodes cannot overlap placement radiuses. This is to force the players to be organized in their placement of nodes.
- Food: An integer resource the player must balance and accumulate, all the game's objectives pertain toward acquiring a certain amount of Food. Food is limited by the presence of Food Silos and are stored in them. Certain nodes, such as plants, produce food over time. Food will also act as currency to progress the game and to place down other nodes. Food is also measured on the scale of 1-1000 units at any given time.
- Nitrogen Content: Also called "Nitrogen", this integer is how much nitrogen exists balanced out in the in-game environment. It represents fixed nitrogen in the soil. Nitrogen Content is produced and reduced by the players actions and can range from 0 (nitrogen deficiency in the environment) to 100 (nitrogen excess in the environment). Nitrogen content is best kept at value 50 which is healthy and average.

- Runoff: Excess nitrogen that is damaging the environment, this scales with the amount of nitrogen content in existence. This is represented as an integer of 0-10, 0 being no runoff and 10 being maximal runoff. Getting a 10, results in an automatic game over. Nitrogen runoff will hurt the environment, the higher the number the higher the intensity of drawbacks. Examples of how runoff could hurt the environment would be the stifling of plant's growth between stages, faster exhaustion of nodes, and the negative visual effect on natural spawning nodes.
- Tooltip: A small description given to an element or a piece of content, like a node. Tooltips will be displayed in a certain part of the HUD. Tooltips are visible to the player in both normal play and inspect mode.
- Flavor Text: Any text that does not relate directly to the game's mechanics or technical description of any object and just exists to give a sense of personality to the game's narrative.
- Overhead: Are the statistics that manage the game system separate from the information contained in the nodes. These are directly tied to the game state.
- Exhausted: When a node can no longer function and must be "replenished". In some way. A node must be replenished with fertilizer which would increase the nitrogen content of the environment.
- Stamina: A Measurement of time until the node's exhausted in in-game hours (real world seconds). It is usually only plants that get exhausted. Once a plant is exhausted, a player must tap on its node to re-fertilize it. Once this is done this will add more nitrogen content to the environment. Stamina represents the time it takes for fertilizer to be completely consumed.
- Player Built Node Limit: This statistic is raised by completing achievements and it's the hard limit of how many nodes the player can place down on the map.
- Map: This is the part of the screen where the player places down nodes. The map is effectively a canvas, and the placement of nodes is relatively free form on a 2D axis. This map is essentially the player's farm which they can maintain.
- Minigames: These are minor games that are entered into from the main in-game screen. When the player plays minigames, it does not pause the game world. Minigames are different based on what context they are launched in. The types of minigames that exist are based on implementation. If the player successfully completes a minigame they are rewarded. Minigames will usually draw thematic inspiration from smaller processes in the real-world nitrogen cycle. Minigames should only last for 10-30 seconds ideally. Specific minigames are attached to specific nodes and are entered into by tapping a node with a certain notification.

- Gameplay Loop: The set of actions that the player repeats until the game is finished. The standard gameplay loop revolves around the player placing down initial nodes, gaining food slowly over time to buy more nodes. In the environment, there are random events, such as weather, which can happen without the player predicting it and could influence the player's farm. The player must learn how to react to these random events. When the player does well enough or fulfills an in-game objective, they can receive in game rewards which help bolster the productivity of their farm. These in-game objectives ought to be achieved in order as they help guide the player along. All events and statistics the game has are linked to how many hours progress. This includes random events.

Node Entity Definitions: To go over the types of nodes a player can build on the map. The amount of information that pertains to a node will most likely be expanded in later iterations of the game.

- Potato Plant: A basic plant that would have multiple stages of development and produce a certain number of foods overtime. To increase the rate of food production, the player would place more of these. The cost for placing a potato plant would consume nitrogen content from the overall pool. Potato plants, like all plants, have a stamina bar for the time it takes until they are exhausted and need to be fertilized. A plant that is not fertilized will not produce food. The placement radius for a potato plant is small so it allows groups of potato plants to be placed down close together on the map.
- Food Silo: Stores food and increases the Food Cap. The discrete purpose of Food Silos is to pace the game and make sure the player does not progress too quickly. This is also an encouragement for the player to spend food as opposed to wasting it overtime.
- Denitrifier: This node does not have any specific real world parallel. It is most like a remediation tool to remove nutrients from the in-game environment. It is a fictional machine which is supposed to decrease the nitrogen runoff in the environment by 1. Can be placed anywhere on the map. This will also have a statistical effect on certain nodes and a visual effect on certain nodes, like ponds. Which will have less algae bloom when affected by the denitrifier.
- Statue: There will be many nodes of this type, but this statue is just a decoration which the player either earns as a reward or purchases with food. There will be many statues representing different things. Its existence is meant to add some humor to the game.
- Ammonia Silo: This node can explode on random chance due to certain random events triggering. This silo increases the production of all adjacent nodes by 1 within a certain radius. When an ammonia silo explodes, the Runoff gets permanently raised by 5. This node is meant to add a high-risk high-reward element to the game.

- Natural Nodes: These nodes are effectively placed by the game state and their placement is outside the player's control. Some do not have a bearing on the game state and only serve to be inspected by the player for some educational content.

Random Events: To throw some randomness in the game, there is a random events table the game randomly rolls after a certain amount of time has passed. A minimum of time must pass between the next random event before it can be rolled.

- Heatwave: causes the Ammonia Silos to explode on a random chance for each silo individually. This also causes a random chance in all plants to be killed (removed from play).
- Bountiful Harvest: A random food bonus granted to the player.

Upgrading Nodes: This system governs the way certain nodes change over time. Some nodes upgrade autonomously while other nodes must be upgraded by the player with an investment of Food.

- Plant nodes: All plants have 3 stages, Seedling (S), Young Plant (YP), and Adult Plant (AP). Seedling produces no food and needs some time before it turns into a Young Plant. Young Plants produce a small quantity of food and get exhausted slowly. After some time, it turns into an Adult Plant. An AP produces a large quantity of food and gets exhausted often. The nitrogen content demand for each stage of the plant will be relative to the plant species.
- Food Silos: The player can spend Food to upgrade the capacity of an already existing Silo. Upgrades with 3 Progressive Stages. Food silos require the same amount of food as their added-on capacity to upgrade.
- Ammonia Reactor Silo: Also, just called an Ammonia Silo. The player can spend Food to upgrade this building to bolster productivity of the surrounding farms and to decrease Runoff if it explodes. Upgrades with 3 Progressive Stages. Upgrading also decreases its chance to explode when a heatwave occurs. Its radius length will be specifically determined based on implementation.
- Performance Rating: This is a statistic that appears on the player's device when he has completed all in-game objectives at the end of the game. It is primarily based off the amount of nitrogen runoff of existence when the game ended. The lower the nitrogen runoff, the better the performance rating. The rating will vary based on implementation, but it would be coupled with flavor text as well as raw statistics.

Game System and Loop

With the terminology and the entity definitions defined, on the information processing level and gameplay loop level the game follows an algorithm which repeats until specific goals are completed by the player. The game requires an advisor to be present to give out QR codes for the students. This game system ruleset will assume there will only be one player and one mediator in a session. Every in-game hour is effectively a round that update's stats from the previous round. It automatically progresses in real time. A player can perform an action in the environment at any point in time if they have enough resources to fulfill the cost of that action. Before the game is played it is recommended that the players and the mediator should already have some knowledge about the nitrogen cycle.

Game Setup: When the game system starts up for the first time, at time being 0. The game sets up and keeps track of these global variables: Nitrogen (N2), Food, Runoff, Hour (time), Plants, number of food silos, number of denitrifiers, number of statues, number of ammonia silos, number of non-player-built nodes like ponds and bacteria stored separately. Nitrogen, Food, Runoff, and Hour are variables that are known and visible to the player on the HUD. The mediator should place down the QR codes that correspond to natural nodes and the player should scan those in. After that is done, the game should automatically start, and the Hour counter will start keeping track of time. The player continuously interacts with the mediator as they play the game. Resource transactions to scan in nodes will automatically deduct that resource and be managed by the overhead. The starting values for resources are Nitrogen at 50, Food at 0, Runoff at 0, and Hour at 0.

Game Loop: During the actual main gameplay loop. The game system will constantly be performing the same series of checks every 1000 milliseconds at the end. This should be the rate regardless of the implementation. After every 1000 millisecond state check, the game checks the map for the nodes on it and then updates the overhead statistics. These checks happen so fast to the player that it gives the impression that everything happens in full real time. Nodes effectively have the largest effect on the overhead statistics. Once a node is placed its effect is constant and permanent. The game parses information on the map in this order during a check:

1. Map with a certain number of nodes knows all nodes on it from the last check.
2. Overhead checks to see if there are any new nodes placed in the last hour.
3. The game checks to see if these nodes can be scanned in. If so, the cost is deducted from the overhead. If not, then it does not allow that node to be placed.
4. The game adds these nodes to the roster of nodes that already exist
5. These nodes individually are assigned their starting stats by the game.
6. Their effect is now kept track by the overhead.

7. The game then proceeds upkeep of all the nodes in hierarchy order by type. This order will depend on the specific implementation. The upkeep is usually just the effect that the nodes have applied to themselves.
8. Upkeep then applies upgrades if there were any made that turn.
9. The nodes update themselves.
10. The game then checks if any random events occur on a random die roll. It will also keep track of how much time has passed since the last random event.
11. Game has a normal play resume for 1000 milliseconds and then repeats the check.
12. At any point during normal play, a player can enter a minigame which would provide resource bonuses if succeeded. Minigames are only supposed to last 10-30 seconds. However, the game world still progresses even as minigames are being played.

While the game mechanistically does this. Outside of the mechanics, the player can request to the mediator that they want to place down a node. The mediator is encouraged to ask questions about the nitrogen cycle and should wait for the student to answer the question before they give a node. If the student answers incorrectly, the mediator should not hand out a node. However, if the student answers correctly, the mediator should give the QR code to the player and they should scan it in. This back-and-forth engagement between the students and the mediator should be continuous for the duration of the game. Between each question, the mediator should wait some time before answering the next one. Easier questions should pertain to nodes that are common, like plants and silos. Nodes that are rare like Ammonia Silos and Denitrifiers should only be given out on harder questions. It is usually the student's responsibility to ask for a node, however the mediator's job is to guide the game, so it is valid for the mediator to push the game along if the students are playing with poor strategies. The mediator should also just ask questions to the students about how they are doing in the game. The goal is to make the game have a social component in a group environment between the students and the teacher and not just have the game be played solitary. It also provides a contrast between the harder mechanical interface of the game and the social and educational aspect. So, a student might not be so good at playing the harder mechanical aspect of the game but is able to understand the science of it well and can be rewarded for that.

The game should only be around 20 minutes long for someone to play until they fulfill all the objectives. There is no time limit in the game, the player is encouraged to play at their own pace. Once a player wins, they should either play the game on free play, or just stop playing as the game is over. When the player finally ends the game there will be a "performance rating" granted to them based on the amount of nitrogen runoff in the environment. The lower the runoff, the better the rating. The exact scale of the performance rating system will vary based on implementation. These are the most basic rules and link between the digital side of the game and the social side of it.

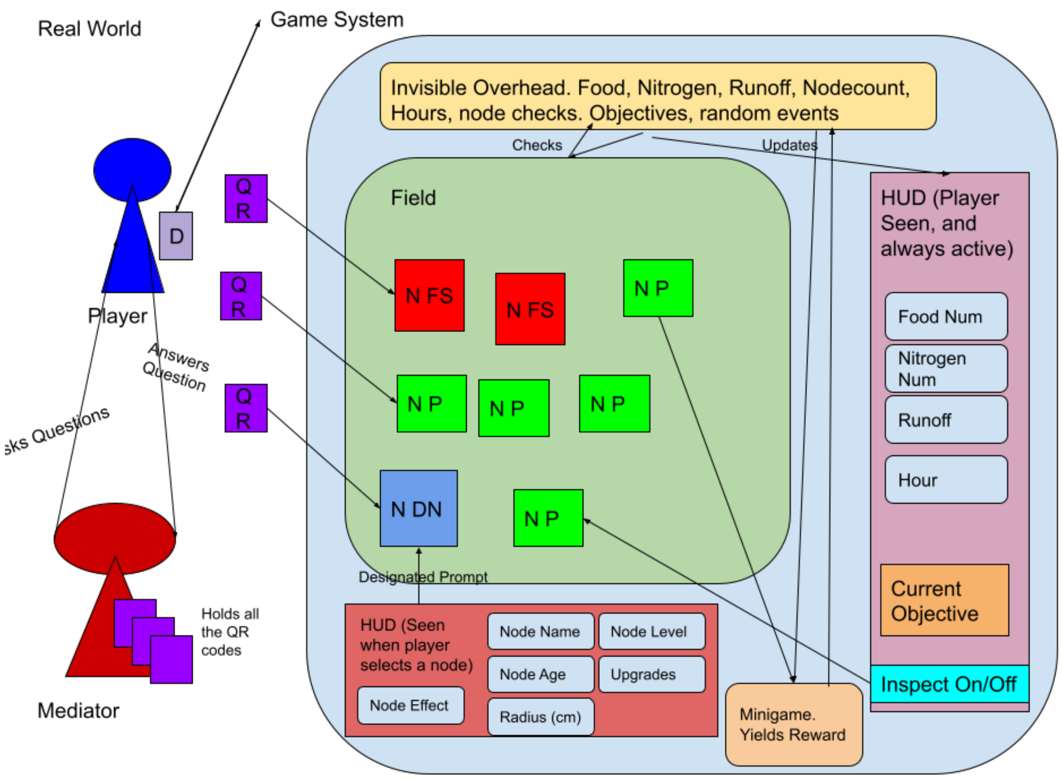

Figure 2.2 Illustrates a simplified mechanistic diagram of the overview of the ruleset with partial implementation with the AR system.

Figure 2.2: Mechanistic Game Systems Diagram. Key: D - Device, QR - QR code, NFS- Node Food Silo, NP - Node Plant, NDN - Node Denitrifier. The designated prompt just demonstrates the gameplay. The inspect mode as seen on the HUD will allow the player to view the science of a node. The Overhead is not part of the field object itself, however it just manages the field and partially gets to display what is rendered on the HUD. Each node has a designated prompt that is assigned to it which is viewable at any time by clicking on the node. Specific QR codes correspond to specific nodes in the game. The current objective to be completed for the player is placed on the HUD. However, the game keeps track of all objectives in the overhead at once. The player is never aware of what exactly is going on in the overhead. If a QR code is scanned in as a node, the device will memorize it even if the camera of the device is oriented away from it. If two QR codes are too close to each other, that is if the radii of the nodes overlap. They will just stop production or functioning until the player moves them away from each other. When this occurs, a prompt should appear as a warning to the player to move those nodes apart.

In Game Objectives

These objectives are meant for the player to be able to reference their progression in game at any time. They are mechanically built inside the game system. Objectives are meant to be completed in the specific order set out to them by the game but are supposed to be logically independent of one another. These should be used in tandem with smaller and more specific objectives. These objectives are meant to reward the player with resources in-game, but the rewards are most likely going to vary based on implementation. You effectively win the game by completing all objectives. You lose the game if you reach the losing condition of 10 Runoff. Losing forces, you to either exit or restart the game. All objectives will be implemented based on the same JavaScript class. With the current prototype of the game, all objectives would most likely be reachable within 20 minutes of playtime. The original progression path for how objectives should function will look like this, but it is subject to change:

1. Build/Scan a plant.
2. Produce 10 food from the farm.
3. Replenish a plant with fertilizer.
4. Inspect 3 different nodes
5. Produce 50 food.
6. Produce 100 food
7. Produce 200 food
8. Produce 500 food
9. Produce 1000 food
10. Freeplay

These basic rules listed above have their implementations explained in the next section. These rules are kept abstract to allow some flexibility for changes in a specific implementation. In the exact implementation there will be information added to or changed from the proposed ruleset, but the general ideas and dynamics would be similar.

2.5.7 Education and Diegetic Storyboard

This section will explain the rationale and the narrative significance for all the elements, what they represent as symbols and what they should represent diegetically. Diegetic refers to the relation of artistic elements that are perceived as existing within the world depicted in a narrative work. Because this game is an example of educational entertainment, it attempts to simulate and emulate the cycle. The "feeling" of correct simulation and emulation in the player's mind is an extremely complicated goal to achieve because it relies on the player's immersion and understanding of the subject matter. However, games, like all art, have authorial intent endowed by their creator. So, we can explain what mechanics were made to represent and how that should tie into the educational material.

Our game does not have a protagonist character or a concrete plot for the audience to follow. This means there is very little narrative explicitly told to the player. Rather, the intention is for the player themselves to be the protagonist of the world of the game. This player-protagonist has the perspective of a farmer trying to maintain their farm. The reason why we chose the player to be a farmer was that they were essentially people who affected the nitrogen cycle directly and the concept of farming is intuitive as a game loop. Farmers effectively feed the world and it is a good way to communicate to the player that responsibility "rests on their shoulders". There is no emotional or personal arc that the player goes through. All the game's focus is on the action the player causes. Effectively the player constructs the narrative for themselves. Getting a game win or a game over is essentially an end to the narrative.

The games are not meant to be lectures, players are meant to learn things not only about the game but also its theme by playing the game. Active participation in a game can allow the players to make connections between different themes that they otherwise might have missed in a conventional lecture [24]. A player who does not know much about the nitrogen cycle can play this game and witness high nitrogen runoff in their environment and watch the other nodes suffer harmful consequences. In the player's mind, connections should be made between seeing the high amount of runoff and the ill environment. In the game's ruleset, the Pond node is one such element made to exemplify if the nitrogen runoff is too high, as it will change its graphic to being filled with algae, which gives off a sickly impression. Algae bloomed waters in the real world are often prefaced with being toxic and a lack of animals in them. When people play games, they do not consciously think about playing the game essentially being the same as learning the game or its themes [19]. However, that is exactly what happens when people play games. People learn the themes and rules of games just by interacting with their elements and forming connections either overtly or subtly, often in tandem. While our game does have an inspect mode which details the science of individual elements. The actual big picture of the social implications of the game are found outside of the inspect mode, through the player's own actions. An example of this is the win/lose screen and the performance rating. Where the player gets their actions in the game evaluated by metrics within the system itself. This performance rating evaluates how effectively the player preserved the environment and gives a value judgment along with other performance statistics. The player is meant to take the performance rating to be equivalent to how sustainable their farming operation was to the nitrogen cycle. A low performance rating should make the player feel regretful for what they did, where a high rating should make the player feel congratulated. The performance rating could also hint at implications that happened in the world of the game after the player has finished farming. For example, if a player had a nitrogen runoff of 8 but was able to reach 1000 units of food, the performance rating will tell the player that they need to farm more sustainably because their farming has accidentally poisoned reservoirs for drinking water with fertilizer runoff.

Why create a game system built over units of information nodes? The reason why this is done is so that we want different representations of real-world objects to be clearly defined and have a specific purpose. Industries that are very multifaceted like agriculture usually parse out their production process into smaller steps or structures. It was only natural that we would design the nodes to be reflections of this real-world process. Plants have their own node because they do a single unique thing in the farm, which is to absorb nutrients and grow food. Silos should be a unique node because their sole purpose is to store food. The reason why every node has one specific utilitarian function applied to itself is because it is much easier for the player to understand its purpose. Individual plants were chosen as an element to represent the most basic form of food production because they are intuitive to image on a large scale. This would also somewhat make it feel like you were working more closely on a farm as opposed to just taking an overseer role. Food silos are not part of the nitrogen cycle directly but are a part of real-world food production because good food storage will actually affect how much food you will need to produce in the future in the real world.

Why have some nodes been natural and produced outside the players control? These nodes are meant to represent the already existing environment that was present before the player started building their farm. They are not utilitarian in function, but instead serve as a marker for how the world is being affected by the players involvement. The graphical effects the natural nodes should correspond to the amount of runoff there is present in the environment. plants should grow excess foliage at lower stages of runoff and start withering at higher stages at runoff due to the lack of other nutrients being consumed alongside nitrogen. Ponds should be depicted as having a healthy level of algae bloom increasing to a destructive level which completely covers the pond.

Creation of a virtual nitrogen cycle. The game's systems should not merely represent itself but represent a hypothetical nitrogen cycle. The nitrogen cycle based on the game's ruleset is reflected in Figure 2.3. This constructed virtual nitrogen cycle is not as nuanced as the real-world cycle but is a basis for understanding the real-world model. It essentially opens the opportunity for the player to learn more about the cycle.

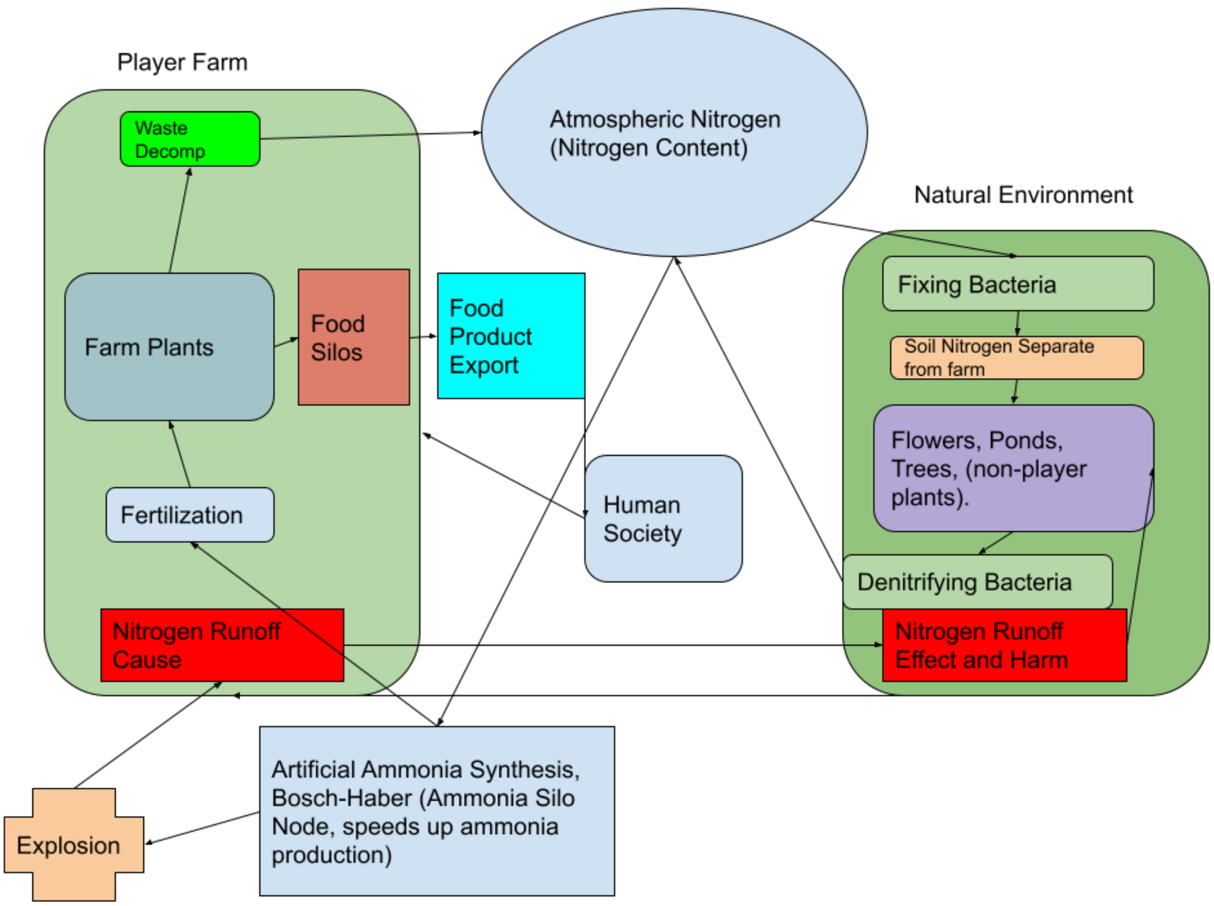

Figure 2.3 Diegetic Diagram of Game World's Cycle.

Effectively, this is what the game's virtual nitrogen cycle would look like mapped onto real world science. The atmospheric nitrogen is really where the system starts. There is a closed nitrogen cycle between the atmospheric nitrogen and the natural environment. However, there is also a closed nitrogen cycle between artificial ammonia synthesis, the atmospheric nitrogen, and player's farm. Both player's farm and natural environment contain a fixing agent, a plant of some kind, and a denitrifying agent. However, the farm's agents are usually enhanced by artificial agents like fertilization and the artificial denitrifying. The farm requires fertilizer because it is meant to produce a surplus of food for an external population, as represented by human society. Human society then builds and upgrades the farm to produce more food for itself. The amount of fertilizer that needs to keep being produced increases and thus the artificial ammonia synthesis must produce more. Ammonia synthesis does rely on atmospheric nitrogen to function and thus requires it to be within the cycle isolated with the farm. Nitrogen runoff is caused from the farm but has most of its harm take effect in the natural environment. Fixing the runoff would require fixing it at the farm.

Random events are systematically determined by the game. They exist to account for the real-world unpredictability of weather and accidents. A real security or safety engineer will most likely experience problems they did not expect with the reliability of a project when working on site. These exist to teach the player that the industry must be prepared for problems it did not expect. Ammonia silo explosions are one such accident that cost many human lives. Players in the game should learn how to create solutions to work around such problems and minimize the damage done by them when they occur.

These examples provided are not exhaustive of all possible points of meaning inside the game. However, these are certain points that are important for the player's association of the game's content to the teaching material and the greater social implications.

2.5.8 Implementation of Prototype

The prototype was built with a combination of HTML, CSS, and JavaScript with the ReactJS library. The website itself and the game were designed independent of each other. Each group member developed the game in their own environment and pushed their work in increments to the repository. The project should run the same on a Windows environment and a Mac environment. The GitHub repository (repo) for the source code to our work is: https://github.com/IQP-NCPOGD/experiments. There is a main branch, which houses the game's most finalized features, and a cycle branch which has certain experimental features which pertain to the game. The group members have their own local directories for the project and are free to pull and make changes. Here, the more significant aspects of the implementation of the prototype will be exemplified.

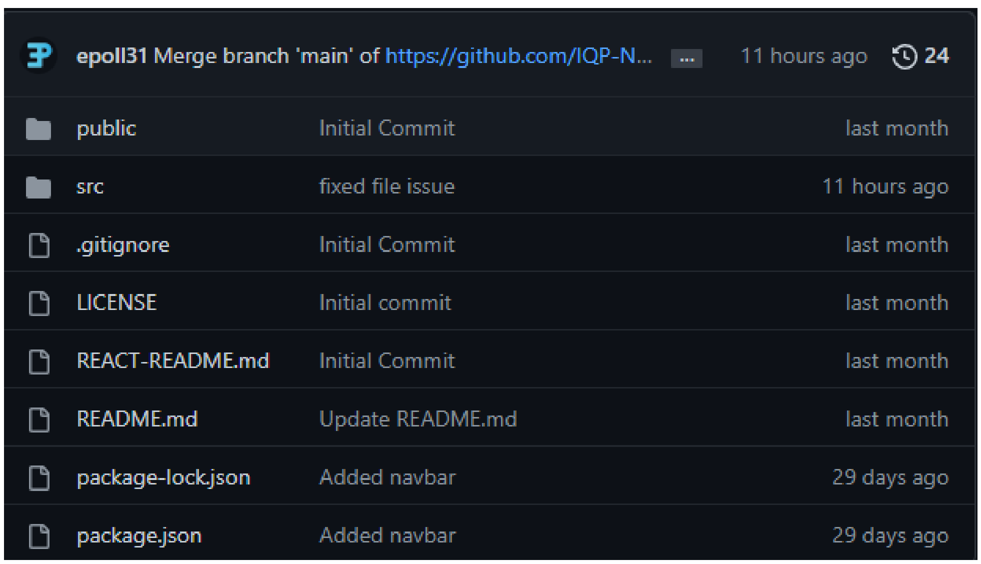

Figure 2.4

Repo on GitHub. The immediate listings of the directory for our repository on GitHub, updated for the December 7th testing session with the BGCFL students.

With the library for ReactJS and the "react-router-dom," module already installed in the web application's directory, the working web application directory should look like this. The directories "build" and "node_modules" are separate from the contents of the repository. To start up the web

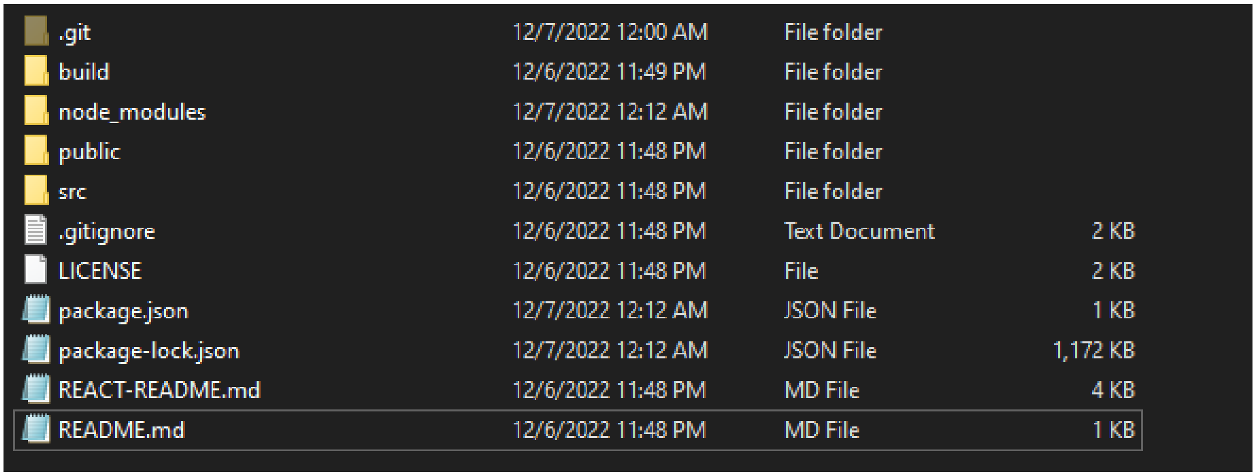

Figure 2.6 Local directory, pulled repo with the React libraries and modules installed.

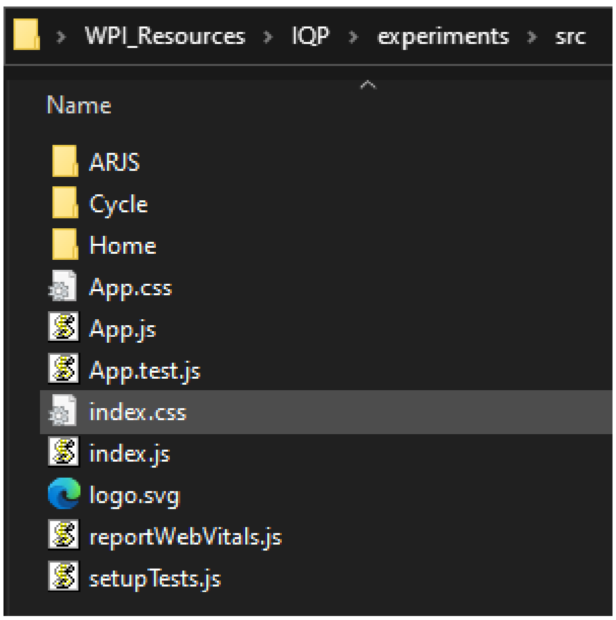

Figure 2.5 src Directory, the "src" directory's contents, this is where the bulk of the webapp is stored.

server on the machine's localhost, open CMD Prompt or another shell in the project directory and enter in the command: "npm start". This should run the app in your default browser.

The directory "build" contains generic icons, logo PNGs, a manifest.json file, and a robots.txt file. The directory "public" contains a copy of the contents in build. These are all generic to ReactJS and are unimportant for the IQP. The directory "node_modules" contains the library for ReactJS and all other modules used. This includes react-router and react-dom. This is present in every ReactJS application, and it is not an essential aspect of the game. There will be many calls to this library in the program we wrote. The "src" directory (figure 2.6) contains all the code we wrote for the web application. "Src" is shorthand for "source code".

In this directory, there are 3 subdirectories which contain the JavaScript code for the separate web pages. "Index.js" is the file that is run first as a script in the browser, it corresponds directly to the home directory. The directory ARJS is where we were going to implement the augmented reality capability for our project. However, we did not get to that in B term and the directory contains a barebones functioning JavaScript page and its corresponding CSS stylesheet.

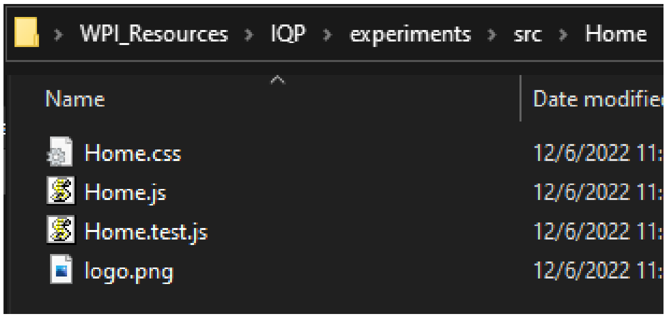

Figure 2.7 *The "Home" directory, contains all the code for the homepage.*

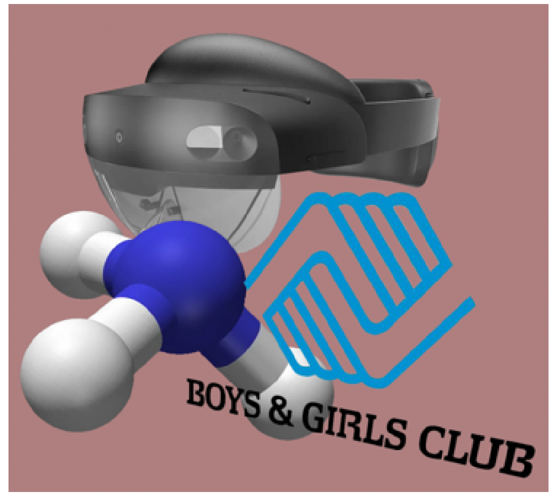

Figure 2.8 *Web Logo. Logo.png is designed by IQPNC. We are most likely going to revise it later.*

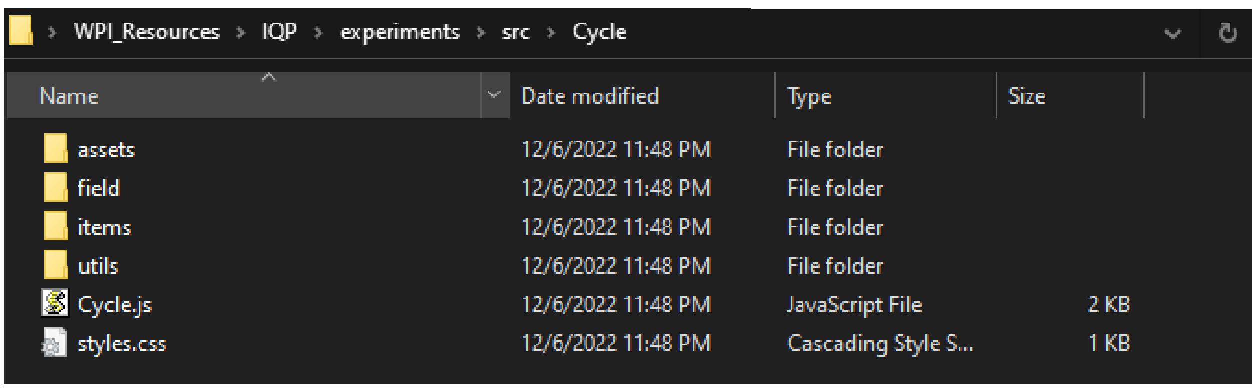

Figure 2.9 *The "Cycle" Directory, contains most of the information for the game's state and overhead systems.*

The "Home" directory (figure 2.7) would be where all the code for the homepage would be stored. As of the end of B term. "Home.js" is the default script for this page "home.css" is the styling.

For the prototype website logo.png (figure 2.8) was designed by the group to be displayed on the homepage.

In the "Cycle" directory (Figure 2.9) there are 4 subdirectories. "Cycle.js" is the root of the web page and lays down the basic rules for the game system. It imports content from the "field", and "items" directories and styles.css. The Time mechanic is also implemented in this file. Time is counted in milliseconds. One hour in the game is roughly 1000 real world milliseconds.

This block of code defines the game state. It is nested within the Cycle class which is an extension of ReactJS's component. The game counts every node individually, only the "food" variable is known to the player in the prototype. The variable "n2" is how much atmospheric nitrogen exists, its default value is 50 as the game requires there to be an amount of atmospheric nitrogen present. In the prototype, all the systems that relied on "n2" were only partially implemented. The counter for "ponds", "trees", and "flowers" nodes exists but the nodes themselves are not implemented. There is also no maximum limit for how many nodes can be on the map defined. The player can place down as many nodes as they want. If the map were infinitely large, the player could place an infinite number of nodes.

```
this.state = {
  hour:    0,
        farms:  0,
        foodSilos: 0,
        dentrifiers: 0,
        statues: 0,
        ammoniaSilos: 0,
        ponds: 0,
        trees: 0,
        flowers: 0,
        nbc: 0,
        dbc: 0,
  food:    0,
```

Figure 2.10 Cycle Variables, game state variables in Cycle.js

The "assets" directory contains all the sprite graphics for the game. Every sprite is in ".svg" format as it is a vector-based graphic and is scalable to different resolutions. The other JS files access this directory to render the graphics.

Field.js	12/6/2022 11:48 PM	JavaScript File	5 KB
FieldItems.js	12/6/2022 11:48 PM	JavaScript File	5 KB
styles.css	12/6/2022 11:48 PM	Cascading Style S...	4 KB
useFrameTime.js	12/6/2022 11:48 PM	JavaScript File	1 KB

Figure 2.11 Field directory. Contains more implementations meant to be used in the cycle wrapper.

```
const handleDrop = (e) => {
var data = e.dataTransfer.getData("text/plain");

    let item = {
        x: e.clientX - offset.x - 50,
        y: e.clientY - offset.y - 50,
        type: data,
        radius: 200,
        age: 0,
        start: Date.now()
    };
        switch (data) {
        case 'foodSilo':
            item.level = 1;
            break;
        case 'potato':
            //potatoes per minute
            item.ppm = 5;
            item.radius = 100;

            setInterval(() => {
                const newState = state;
                newState.food += item.ppm / 60;
                setState(newState);

                //console.log('food:', state.food);
            }, 1000);
            break;
        case 'denitrifier':

            break;
        case 'ammoniumSilo':
            break;
    }
```

Figure 2.12 Drag and Drop Code. some code in Field.js to handle the placement of nodes.

The "field" (figure 2.11) directory contains the code for the game's Field element. Field.js handles the statistics of instantiated nodes and their upgrades. It also handles node placement and draws radii around nodes as what is shown in figure 2.12. The JS file "useFrameTime.js" handles the game's simple animation, even though in the prototype the sprites do not have more than one frame of animation. "FieldItems.js" handles the information unknown to the map but internally to the nodes themselves. Each type of node has its own implementation there. It is also worth noting that each node has its own self-reported age, this is because nodes are supposed to upgrade asynchronously. The potato plant node autonomously creates 1 food every 5 seconds. The food silo starts off with a capacity of 25 food and can be upgraded by spending 25 foods for a +25 to its capacity.

In the "item" directory there is the file item.js (figure 2.13). This file exists to handle the data transfer from the items UI bar in the game. In the "utils" directory, the template for a progress bar for the HUD was partially worked on but nowhere near completion.

Most of the code documentation is in the form of comments inside these JavaScript files. The figures above do not show all the code, only specific highlights that were important to the project.

```
return (<div    id='field'
                        className='field'
                        onDrop={event => handleDrop(event)}
                        onDragOver={event => handleDragOver(event)}
                        onMouseDown={event => handleDragStart(event)}
                        onMouseUp={event => handleDragEnd(event)}
                        onMouseMove={event => handleDrag(event)} >
                <div className={'menu food' + (foodMenuActive ? ' active' : '') }
                        onClick={handleFoodMenu}>
                    <h1>Food: {Math.floor(state.food)}</h1>
                    <CapacityData items={items} />
                    <PotatoPlantData items={items} />
                </div>
                <div className='items'>
                    { items && items.map(itemToFieldObject) }
                </div>
            </div>
```

Figure 2.13 Drag and Drop Wrapper. Code from Field.js that maps the drag and drop interface.

2.6 Methodology of Testing with the Students

On December 7, 2022, the group went to the Boys and Girls Club of Fitchburg and Leominster. There was a schedule for our time with the students. It was not necessary that the schedule be followed exactly, but it was important that all the tasks get completed. This would be the only time we would be able to have a long session with the students in B term. The instructions were:

Tasks when we meet the students:

- 3:00 Setup the game computer's our computers. We should have 3 computers running the game and a form ready to be filled out. Everybody will run the game from local host
- 3:30 Introduce us to the students and give our background.
- 3:40 Banter with the students for a little bit
- 3:50 Give introduction on the prototype and instructions on what to do. A printed set of instructions should be at every station where we play the game.
- 4:00 Demo the game
- 4:10 Test the game, 10 minutes of playtime for each student, students should be advised by an IQP group member. then right after each user's session have them take the quick survey.
- 5:00 Show the kids some of the code of the game and website. And talk about computer science.
- 5:40 Talk a little more about the science behind the nitrogen cycle and why it is important.
- Closing banter
- 5:50PM-6:00PM We pack up, say our goodbyes, and leave.

To-do after we have the meeting:

- Compile the data in the spreadsheet
- Write the rest of the IQP report
- Fill in the citations on the IQP report
- Style the IQP report.

Accidentally, the original sample of 6 students that volunteered to test the game were unable to attend the feedback session. Because the identities of the students and the specific size of the sample were not important to the test, we were able to quickly find 9 different students to volunteer for testing. The game was demonstrated with those students. Our original plan was to have the entire group of 6 students play the game at once and then take the survey. With our group size being changed last minute, we had to deviate from the original instructions.

For our setup, we reserved a small classroom, at the Boys Girls Club of Fitchburg & Leominster building. The group had brought their three personal laptops with them. These laptops did have different hardware specifications and operating systems, but that would not affect the actual performance of the game.

As soon as the students came into the testing room, we would give them a brief lesson about the nitrogen cycle, the purpose of the game, and how to play. We would test the game with just 3 students simultaneously with the aim that they would play the game for 10 minutes and then finish the survey quickly. Then after the survey, as part of engagement with the students we would give a live programming demonstration by exemplifying the source code to the game on a monitor. We effectively repeated the process with 3 waves of students. The testing ran from 4-5:30PM. At 5:30PM we finished collecting feedback with all 9 of the students. Shortly after we shut down our setup.

2.6.1 Instructions to Play

These instructions are different from the ruleset as the ruleset lays down everything in the game, including things that the player should not obviously see or know. The instructions just give the player the directions on how to play the game. A screenshot of the game the students played is figure 2.14. The Instructions we issued were:

Introduction:

The WPI IQPNC Group's prototype is a simple city builder game about the real-world nitrogen cycle. This is a Farm-Builder game where you are a farmer trying to grow food while also keeping the environment healthy. After you play the game for 10 minutes, you will take a short survey on your experience.

Tutorial:

1. When on the Project's website homepage, click the "Nitrogen Cycle" tab to start up the demo. You should see a blank map and statistics as well as the buttons for placing down nodes.
2. The Data tab is what keeps track of the statistics in the game environment, the nodes you place down will affect these statistics. Once a node is placed it is placed down forever.
3. In the Data Tab there are a few resources: Food is the most important stat, the more food you produce the better.
4. Place a Food Silo down.
5. Click on a node to see its statistics. Each node will have different statistics.
6. When a specific statistic turns green, that means you can upgrade it.
7. Experiment around by dragging and dropping different nodes onto the canvas.
8. Certain nodes do certain things. Farms produce food over time, Food Silos store food.
9. The Ammonia Silo will bolster the productivity of the plant nodes in its radius.
10. Each node has a radius of placement away from each other.
11. The goal is to produce as much food as you can. So, relax and enjoy the city build

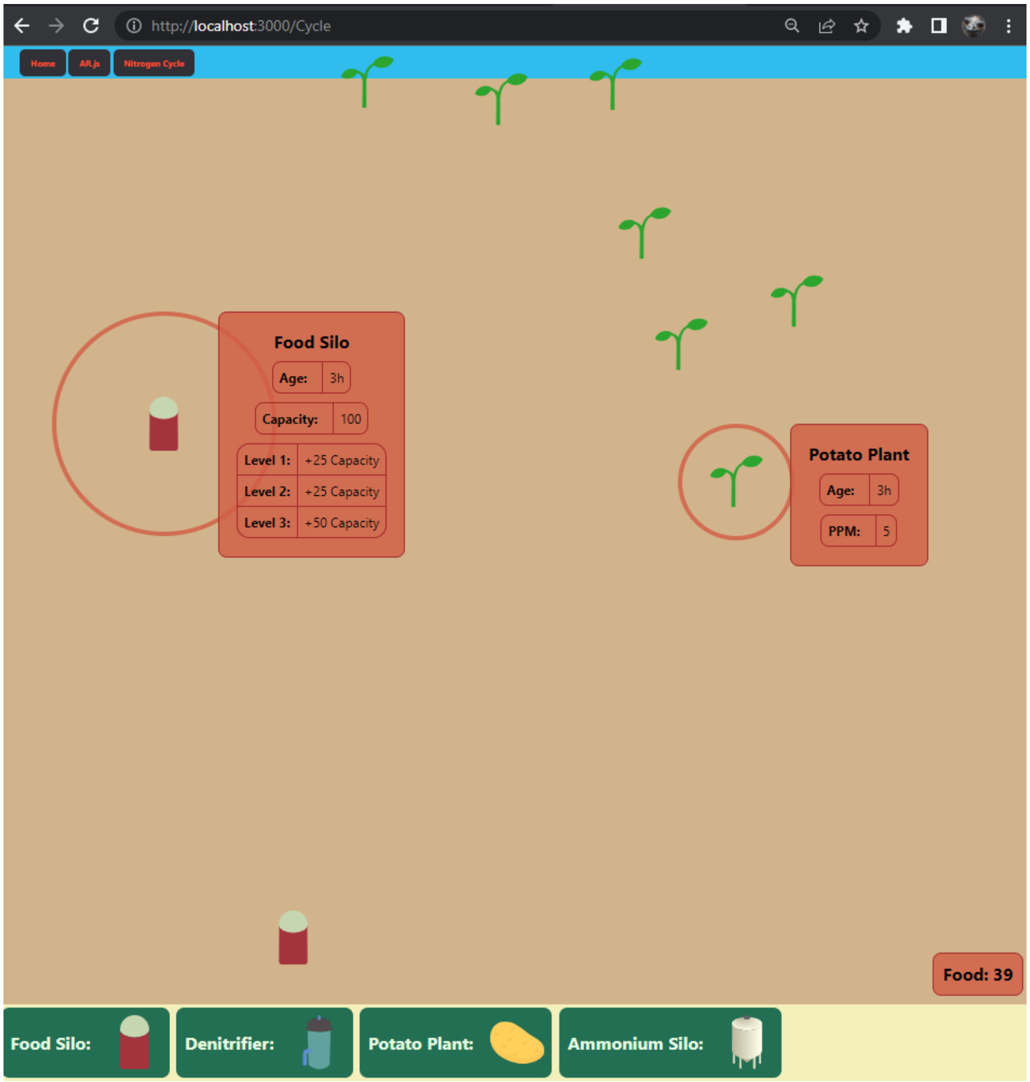

Figure 2.14 *Playing the game. Example gameplay in progress, each node keeps its own age as displayed by the red tab. The red circle around each node is effectively an anti-placement radius. You cannot place another node in that circle.*

2.6.2 Survey (that was sent out)

This section below contains the survey that was sent out on December 7th, it should contain no participant identifying information. The survey was issued via Google Forms. The survey was assigned right after the participants played the game for 10 minutes. The questions were designed with the audience in mind. The proposed script for the survey was:

Simple Diagnostics Questions

Q1: On a scale of 1 (unclear) to 5 (very clear), how understandable were the graphics?

A: (number)

Q2: When you stopped playing, how much food did you have?

A: (number)

Q3: On a scale from 1(too complicated) to 5 (easy to understand)? How complicated did you feel the game was?

A: (number)

Q4: How frustrating is interacting with the game's elements on a scale of 1 (very frustrating) to 5 (not frustrating at all)?

Q5: On a scale from 1 (did not like) to 5 (liked a lot) how did you enjoy the game?

A: (number)

Q6: What would you like to see put in the game?

A: (Text)

Q7: How many nodes in total did you place down on the map?

A: (number)

Q8: How many Plants did you place down?

A: (number)

Q9: How many Food silos did you place down?

A: (number)

Q10: How many Denitrifiers did you place down?

A: (number)

Q11: How many Ammonia Silos did you place down?

A: (number)

Q12: Was the game's pace too fast or slow?

A: (text)

Q13: Why, in your words, do you think the Nitrogen Cycle was important and why?

A: (text)

Q14: What did you learn about the Nitrogen Cycle?

A: (yes or no)

Q15: Did you feel like you wanted to play more?

A: (text)

Q16: Were the game instructions easy to read and understand?

A: (Yes/No)

Q17: How many times did you upgrade nodes?

A: (number)

Q18: What games or types of games do you like to play?

A: (text)

The metrics that would be of most use to us would be the ones that would be able to strictly quantify the game. We could make several inferences about the player's interaction from them. The metrics we collected from the prompts in the survey were: Ending Food Amount, Total Node Count, Denitrifiers Placed, Ammonium Silos Placed, Food Silos Placed, Plants Placed, Feeling of Complexity, Feeling of Frustration, and Graphic Comprehension. The rationale for collecting these statistics is:

- Ending Food Amount: This would give us an estimate of how many Plants and Food Silos were placed and how quickly they upgraded them. When paired against the statistic for node count for Plants and Food Silos, this could give us rates of food production.
- Total Node Count: Since there was no hard limit on the number of nodes a player could place down. Players could effectively have just spammed nodes for their enjoyment. This number would tell us if they had an order for how they would place down nodes. This should be best compared to the quantities of nodes that exist in the other categories.

- Denitrifiers Placed: Denitrifiers had very little impact on the gameplay in the December 7th iteration of the prototype. However, the players were allowed to place them however they wished. This is important to take note of that the Denitrifiers had a radius around them which did not allow other nodes to be placed next to them.
- Ammonium Silos: This is another type of node the player could place. Even though its implementation was incomplete, it is still important to note how many were placed.
- Food Silos: Because Food Silos allow food to be stored and this result in greater total food being achievable by the player. These are expected to be built in parallel with the number of plants that exist.
- Plants: These produce food. These are usually going to contribute to the total amount of food that exists. Plants generate food over time and fill up food silos.
- Feeling of Complexity: Number from 1-5 on a linear scale, with 1 being “too complicated” and 5 being “not complicated”.
- Feeling of Frustration: Number from 1-5 on a linear scale, with 1 being “too frustrating” and 5 being “not frustrating”.
- Graphic Comprehension: Number from 1-5 on a linear scale, with 1 being “very unclear” and 5 being “very clear”.

From the survey collected, some of the feedback was opinion-based and that is not able to be quantified. However, there were also statistics collected from actions in-game that are revealing of how players interacted with it, as shown in table 1. Specific metrics were chosen because they were an integral part of the game's mechanics or interface. Due to the students themselves generally submitting feedback at their own discretion, not all participants answered all the questions. However, most of the participants answered all the questions to the best of their ability. In the table below, any spaces marked with an “-” is either a blank answer or a nonsense answer.

Table 1 Table of Responses based on the survey. The averages are down below. For any average that contained a missing value, we effectively discounted it and left it out when determining the average. These missing values should not impact the conclusions significantly.

Participant Num	Time Played (minutes)	Ending Food Amount	Total Node Count	Denitrifiers Placed	Ammonium Silos Placed	Food Silos Placed	Plants Placed	Complexity (1-5)	Frustration (1-5)	Graphic Comprehension (1-5)
1	10	114	17	0	0	4	13	4	5	5
2	10	300	45	0	1	5	30	5	4	5
3	10	12	20	3	0	4	11	4	4	3
4	10	125	50	6	3	10	31	5	5	4
5	10	203	-	0	-	13	-	4	5	5
6	10	87	56	1	0	13	43	3	4	4
7	10	101	18	0	0	1	17	3	2	4
8	10	100	20	1	0	3	16	3	4	3
9	10	-	-	-	-	2	-	2	5	3
Averages	10	130.25	32.29	1.38	0.57	6.11	23.00	3.66	4.22	4.00

Aside from these numbers, the group also received some qualitative feedback on what the students would like to see from an "upgraded" version of the game. Generally, the participants wanted more node types and a system for non-player-characters (NPCs) like animals and farmers. There were also new plant types requested by the students, like pumpkins. Two students recommended that we implement houses in the game. Most of the students not only mentioned in the survey that they enjoyed the game but also personally thanked us and told us how excited they were to see the final version of the game.

2.6.3 Analysis of Feedback

When discussing the raw game stats, it is important to note that the existence of the nodes causes the increase of the food. While upgrades to silos deplete food. Students would place on an average of 32 nodes and would yield an average of 130 food. A single potato plant would spawn 1 unit of food every 5 seconds, which means that a single potato plant spawns 12 units of food a minute, or 120 units of Food every 10 minutes. There was an average of 23 plant nodes, 6 Food Silos, and 1 denitrifier. Plant nodes cannot be upgraded by the player, but the player spends Food to upgrade the storage capacity of the silo by 25 units. On their third level, food silos can increase their capacity by +50 units. Food will cap off when it reaches the combined storage capacity of every silo present. Generally, we can infer that the players were not attempting to maximize their food amount with knowledge of an optimal strategy and would leave some of their food neglected at a small maximum capacity. Many of the players had accumulated over 100 units of food, while also having a relatively high and stable node count. While testing, even though there was no node limit, we noticed players creating farms with a specific level of organization. An example of this was some players were isolating a section of the map off for placing silos, and other sections for placing plants. We also noticed that in doing this, players took a while to build their farm setups piecemeal and steadily over the duration of the 10 minutes. There were a few players that placed down a bulk quantity of nodes very early and just sat back and observed their farm for the duration of the test. While these behaviors cannot be inferred directly from the table above, those two playstyles would probably have had a significant impact on the results.

There did not seem to be players who naturally did not understand the interface. This could be evidenced by the number of nodes placed down for each player and their ratios. The average for Food Silos to Plants was 6:23, or about 1:4. There were always more plant nodes placed than silos in all participant cases. The player naturally placing more plants than silos was something we were aiming for as a smaller task of this game as that would be intuitive.

Players generally avoided using the Denitrifiers and Ammonia silos, partially because they might have had frustration in placing them down due to their radii being so large or they could not immediately see the point in them. These nodes were already partially implemented but their effects were not. Because of this the players were inclined to avoid them.

The players generally thought the game's rules were very understandable, which is good for a game like this which needs to be understood as quickly as possible to be played in a session with other players. Surprisingly many of the students did not find the interface frustrating. Players also generally thought the graphics were easily comprehensible. This ties into the game's overall readability.

3 Conclusion

3.1 Analysis of Success

The IQP group wishes that it had a more expansive prototype for the students where at least all the nodes and systems planned for the prototype work with full capability. There was also a desire to polish the user interface some more before December 7th. However, the development team did not get to it. Our proposed rule set for our game not only worked well mechanically but also worked well in the minds of the participants. We were also very pleasantly surprised that our participants enjoyed playing our game. The testing went more pleasantly than we expected, and there were no technical problems.

For the project prototype itself, we wanted to get to fully implementing the nitrogen system as well as the Denitrifier and Ammonium Silo nodes. The creation of the prototype itself was only partially successful in that it did not have all the features we planned it to have. However, the storyboard, technical base and ruleset we created did reach its desired iteration in B term. We plan that there will be alterations made to it in C-Term once the actual AR iteration needs to be made. We expect that the ruleset will provide a solid base for development going forth. We do not believe we will ever need to use any external engine other than more JavaScript libraries to complete the game in C term. Some other software may be used to work on engine separate game assets like 3D models, sound design, or sprites.

Overall, we believe that this term was successful in establishing research into the subject matter, a game storyboard, and a working prototype.

3.2 Analysis of Revisions (What should we have done differently)

The IQP team believes that there were some tasks it should have done and others it should have changed regarding the project or prototype at earlier stages of development. We wish we did not spend so much time testing different engines only to later discover that they did not suit our needs. Many of the members were experimenting and exploring around with Unity and other 3D engines. The reason why we could not use those engines is because they require a level of time and dedication to learning them that we did not have at our disposal. We spent so much time in this process that it felt like we were hurting our productivity towards our end goal of making the prototype. Another mistake was trying to develop the ruleset after selecting the engine instead of developing it while we were exploring. That effectively postponed many realizations and compromises that would have happened in a much more efficient way. It felt like to the group the first two weeks were underutilized and wasted because we attempted to learn engines and programming languages that we ended up not using at all in the project, like Unreal, Unity, C#, and Lua. However, now that we are through with the process of deciding technical details. It is not expected that we will spend time pondering which tools to use in C term. To help group members that have the bulk of their work in C-Term, style guides and "cheat sheets" have been written by the B-term group members to assist in working on the project. This is so the group does not fall into the same mistakes again.

The IQP group wishes it had launched an interview with an expert in the field of agriculture or chemistry who could give us insights into how to enhance the project. This could consist of insights into the agricultural industry or an analysis of the problem of human involvement in the nitrogen cycle. These insights could have been used to expand research into more nuanced directions or put some more specific material into the educational side of the game.

The state of the prototype was less than desirable for the IQP group due to many of the proposed features for it not completely working and the lack of polish in the interface. We wanted to fix these issues, but we found ourselves constrained by time and could not remedy them. In C terms these issues will hopefully be addressed.

Overall, the group did not have many things they necessarily wanted to revise but wished they could have retroactively implemented solutions to these problems.

3.3 Greater Implications

The IQP team had much fun working on this project. In C term we hope to do an even better job at delivering a game that is not only entertaining, but educational. Using the emergent technology of augmented reality, games and education have broadened capabilities for what they can do for the student. We look forward to working with the Boys and Girls Club of Fitchburg and Leominster and the STEM Education Center further in the future. Our project's goal is to bring important environmental issues to the forefront of the minds of the future, and we will try our hardest to make sure that becomes a reality.

4 Works Cited

[1] D. A. Hutchins and D. G. Capone, "The marine nitrogen cycle: new developments and global change," *Nature Reviews Microbiology 2022 20:7*, vol. 20, no. 7, pp. 401–414, Feb. 2022, doi: 10.1038/s41579-022-00687-z.

[2] H. Daims, "Complete nitrification by Nitrospira bacteria.," 2015, Accessed: Dec. 11, 2022. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/26610024/

[3] J. Raymond, J. L. Siefert, C. R. Staples, and R. E. Blankenship, "The natural history of nitrogen fixation," *Mol Biol Evol*, vol. 21, no. 3, pp. 541–554, Mar. 2004, doi: 10.1093/MOLBEV/MSH047.

[4] Admin, "Rocks & Minerals in Plant Growth," *Rock & Gem*, Jun. 20, 2022. https://www.rockngem.com/rocks-minerals-in-plant-growth/ (accessed Dec. 11, 2022).

[5] "The Effects of Too Much Nitrogen in Plants." https://homeguides.sfgate.com/effects-much-nitrogen-plants-43755.html (accessed Dec. 13, 2022).

[6] "APPENDIX I CURRENT METHODS OF COMMERCIAL PRODUCTION OF NITROUS OXIDE," *Br J Anaesth*, vol. 39, no. 5, pp. 440–442, May 1967, doi: 10.1093/BJA/39.5.440.

[7] "Fritz Haber - Nobel Lecture: The Synthesis of Ammonia from Its Elements." https://www.nobelprize.org/prizes/chemistry/1918/haber/lecture/ (accessed Dec. 13, 2022).

[8] "Introduction to Ammonia Production | AIChE." https://www.aiche.org/resources/publications/cep/2016/september/introduction-ammonia-production (accessed Dec. 13, 2022).

[9] H. W. Scherer, K. Mengel, G. Kluge, and K. Severin, "Fertilizers, 1. General," *Ullmann's Encyclopedia of Industrial Chemistry*, Jul. 2009, doi: 10.1002/14356007.A10_323.PUB3.

[10] E. Brown, "The guano wars: How the world almost went to blows over crap," *Medium.com*, Jun. 11, 2020. https://medium.com/lessons-from-history/the-guano-wars-how-the-world-almost-went-to-blows-over-crap-d68482983514 (accessed Dec. 12, 2022).

[11] H. Ritchie, M. Roser, and P. Rosado, "Fertilizers," *Our World in Data*, Oct. 2022, Accessed: Dec. 13, 2022. [Online]. Available: https://ourworldindata.org/fertilizers

[12] M. J. Palys, A. Allman, and P. Daoutidis, "Exploring the Benefits of Modular Renewable-Powered Ammonia Production: A Supply Chain Optimization Study," *Ind Eng Chem Res*, vol. 58, no. 15, pp. 5898–5908, Apr. 2019, doi: 10.1021/ACS.IECR.8B04189/ASSET/IMAGES/MEDIUM/IE-2018-041896_0014.GIF.

[13] 1veritasium 1veritasium, "The Man Who Killed Millions and Saved Billions," *YouTube*. https://www.youtube.com/watch?v=EvknN89JoWo&ab_channel=Veritasium (accessed Dec. 05, 2022).

[14] DW News, “Why was the Beirut blast so massive? Ammonium Nitrate explosion explained,” *YouTube*, 2020. https://www.youtube.com/watch?v=MEpFyE_ED7M (accessed Dec. 05, 2022).

[15] C. E. Munroe, “Destruction of Muscle Shoals Ammonium Nitrate by Fire and Explosion,” *Ind Eng Chem*, vol. 17, no. 8, p. 819, Aug. 1925, doi: 10.1021/IE50188A015/ASSET/IE50188A015.FP.PNG_V03.

[16] G. Tessenderlo, “1959 Blast | City of Roseburg,” Nov. 15, 2008. https://www.cityofroseburg.org/visitors/1959-blast (accessed Dec. 13, 2022).

[17] “A Pound of Prevention: Stopping Nitrogen at the Source with Advanced Septic Systems ,” *Environmental Protection Agency*, Aug. 29, 2022. https://www.epa.gov/snep/pound-prevention-stopping-nitrogen-source-advanced-septic-systems (accessed Dec. 05, 2022).

[18] “Causes and ecosystem impacts,” *Centers for Disease Control and Prevention*, Oct. 04, 2022. https://www.cdc.gov/habs/environment.html (accessed Dec. 12, 2022).

[19] M. Voss, H. W. Bange, J. W. Dippner, J. J. Middelburg, J. P. Montoya, and B. Ward, “The marine nitrogen cycle: recent discoveries, uncertainties and the potential relevance of climate change,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 368, no. 1621, Jul. 2013, doi: 10.1098/RSTB.2013.0121.

[20] “About the Fertilizer Industry | TFI | The Fertilizer Institute.” https://www.tfi.org/our-industry/state-of-industry-archive/2016/about-the-industry (accessed Dec. 13, 2022).

[21] N. Beacom, “Farms may depend on water - but they are also polluting it,” *America Magazine*, May 28, 2020. https://www.americamagazine.org/politics-society/2020/05/28/farms-may-depend-water-they-are-also-polluting-it (accessed Dec. 12, 2022).

[22] “Massachusetts Middle School Science Standards — The Wonder of Science.” https://thewonderofscience.com/massachusetts-middle-school-science-standards (accessed Dec. 13, 2022).

[23] “Programming video games and simulations in science education: exploring computational thinking through code analysis: Interactive Learning Environments: Vol 26, No 3.” https://www.tandfonline.com/doi/full/10.1080/10494820.2017.1337036 (accessed Dec. 13, 2022).

[24] T. Khan, K. Johnston, and J. Ophoff, “The Impact of an Augmented Reality Application on Learning Motivation of Students,” *Advances in Human-Computer Interaction*, vol. 2019, 2019, doi: 10.1155/2019/7208494.

[25] “Satellite images of Beirut explosion show massive crater at port | CNN.” https://www.cnn.com/2020/08/05/world/satellite-images-beirut-explosion-before-after-trnd/index.html (accessed Dec. 14, 2022).

[26] “A Brief History of Septic Tanks | Sewage | Wastewater | Treatment.” http://djwl.co.uk/blog/brief-history-septic-tanks/ (accessed Dec. 14, 2022).

[27] “Ihor Bondarenko.” https://ihorbondarenko.com/ (accessed Dec. 14, 2022).