Visualizing Models Driven by Real-Time, Sensor-Based Data: A New Way to Experience the Inner Workings of Ecosystems

Sara E. Remsen
B.A. Dartmouth College (2012)

Submitted to the Integrated Design and Management Program
In partial fulfillment of the requirements of the degree of

Master of Science in Engineering and Management

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

In collaboration with
Responsive Environments at the MIT Media Laboratory

Signature of Author____

Sara E. Remsen
Integrated Design and Management Program
May 12, 2017

Certified by____

Joseph A. Paradiso
Professor of Media Arts and Sciences
MIT Media Laboratory Thesis Supervisor

Accepted by____

Matthew S. Kressy
Director
Integrated Design and Management Program

This page is intentionally left blank

Visualizing Models Driven by Real-Time, Sensor-Based Data: A New Way to Experience the Inner Workings of Ecosystems

by
Sara Remsen

Submitted to the program of Integrated Design and Management, in partial fulfillment of the requirements for the degree of Master of Science

ABSTRACT

This thesis presents the human-centered design and development process for a proof-of-concept technology that visualizes models of ecosystem processes using real-time, sensor-based data. The product of this thesis, EcoFlux, provides a new way for people to experience the inner working of ecosystems by using augmented or virtual reality to explore unseen ecological processes. EcoFlux builds on the existing MIT Media Lab project DoppelMarsh, which is a virtual landscape that changes in response to real-time environmental conditions captured by the distributed sensor network at the Tidmarsh wetland site. EcoFlux is the first of its kind to visualize models of molecular motion and carbon flow in 3D, within the context of the physical site, and driven by real-time data. Whether experienced remotely or integrated on site, EcoFlux can be used to inspire curiosity for visitors, enhance scientific understanding for researchers, and promote community development by demonstrating the value of ecological restoration. As environmental sensing becomes more ubiquitous in our daily lives, this thesis provides a foundation for harnessing human sensory systems to make meaning from abundant information.

This page is intentionally left blank

ACKNOWLEDGEMENTS

To my advisor **Joseph A. Paradiso** for inviting me to be part of this initiative, for providing incredible insights, and for inspiring me to see the world differently.

To **Matthew Kressy** for sharing his passion and vision for a better world through the Integrated Design and Management program.

To the Living Observatory group: **Glorianna Davenport** for her visionary restoration mission and for her patient wisdom throughout the project and **Alex Hackman** for sharing his contagious love for nature and inspiring others.

To the Responsive Environments group: **Gershon Dublon** for his out-of-the-box thinking and willingness to help, **Spencer Russell** for his support and infinite patience, **Donald Derek** for his adventurous spirit and positive energy, and **Brian Mayton** for his quiet help along the way.

To **Gabe Miller** for his brilliant wildlife conservation efforts and for connecting me with the Responsive Environments team in the first place.

To IDM: **Kevin Yuen** for his amazing second opinions, **Maria Tafur** for her unwavering encouragement, and **Ben Coble** for his thoughtful insights.

To my parents **Bill and Jane Remsen** for nurturing my curiosity and love of nature and for always supporting my dreams.

To **Kelly O'Brien** for his support and love.

This page is intentionally left blank

Table of Contents

INTRODUCTION

"Whoever you are, no matter how lonely,
the world offers itself to your imagination,
calls to you like the wild geese, harsh and exciting -
over and over announcing your place
in the family of things."

- Mary Oliver, Wild Geese

Humans' ability to interact with the world is constrained by the physical limitations of human sensory perception: what we can see, hear, smell, touch, or taste. However, there are endless data streams sensed by other animals that are just out of reach of human perception, such as magnetic north, minute air currents, polarized light, or electromagnetic pulses (Figure 1). For the first time, we can begin to document some of these imperceptible elements through distributed sensor networks. Not only can we document environmental data, such as temperature or humidity, but we can also begin to capture how humans interact with these environments. As these sensors become smaller and cheaper, they will quickly become standard tools for interpreting our world and its abundant streams of information.

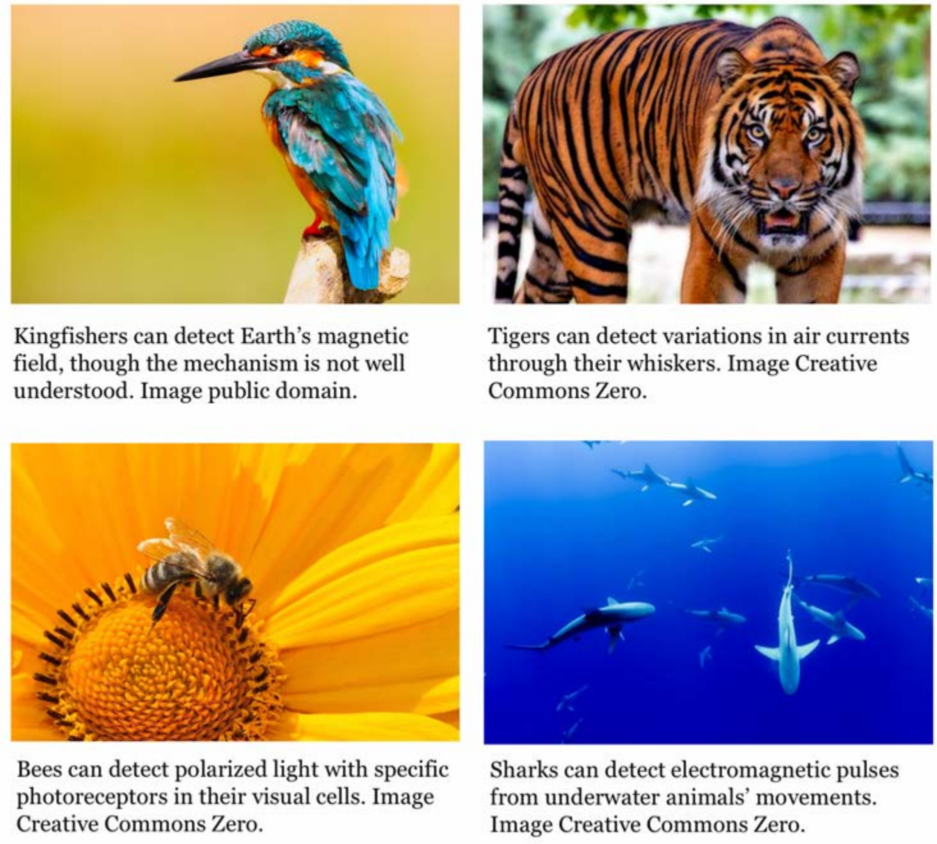

Figure 1. Every animal species possesses sensory adaptations unique to its habitat and ecological function. There are many types of information that humans cannot perceive with our natural biological senses but that can be captured by new types of electrical sensors.

The challenge is making meaning from this wealth of information and presenting it in an appropriate interface that utilizes existing human sensory systems. Most data types are meaningless to us; we cannot feel atmospheric pressure or see in ultraviolet. Presenting this data in a 2D graph enables us to analyze the data, but not to experience it. However, with recent advances in immersive media such as augmented, mixed, and virtual reality, there are new opportunities to communicate and make sense of this "invisible" information. We can use "data viscerlization" techniques [1] to present data in formats that are intuitively processed by human senses. The human brain is exceptional at processing visual information and finding patterns, so spatial visualization is a natural method for communicating unfamiliar data streams.

This thesis explores how spatial visualization techniques can be used to see unseen processes based on real-time data inputs. This work builds on DoppelMarsh, an ongoing project at the Responsive Environments group, which explores the potential of ubiquitous sensing [2]. DoppelMarsh is the result of a collaboration between the Responsive Environments group at the MIT Media Lab and the nonprofit Living Observatory. As part of this collaboration, Responsive Environments deployed low-power sensor nodes throughout the Tidmarsh wetland restoration landscape to collect environmental data in real time. This environmental data is deployed in DoppelMarsh, a virtual reality environment that changes in response to fluctuations in a connected real-world wetland. This synthetic reality can be experienced remotely or even on site at the wetland [3].

The work of this thesis supports the mission of Living Observatory: to tell the long-term story of the Tidmarsh Farms Wetland Restoration and to advance scientific knowledge and public understanding of wetland ecology [4]. Living Observatory is a public interest learning community that complements the large-scale wetland restoration project at Tidmarsh Farms. Restored wetlands provide a myriad of benefits, including carbon sequestration, denitrification, and storm surge mitigation [5]. With the goal of observing, documenting, and interpreting how freshwater wetlands change over time, Living Observatory is uniquely suited to provide insights and create experiences that enable the public to witness how restoration improves the ecosystem. Its interdisciplinary research on the value of ecological restoration is particularly valuable as more landowners take agricultural wetlands out of production and are then faced with a choice: real estate development or ecological restoration for their agricultural sites.

This thesis takes a human-centered design approach to understand the motivations and needs of site visitors, scientists, and the community. Human-centered design focuses on understanding users to design solutions that are tailored to their needs. Insights from in-depth qualitative interviews with important stakeholders were crucial in making decisions throughout the product design and development process, especially in determining the desirability, feasibility, and viability of the final product. This product design and development process consisted of three major phases: research and analysis, concept generation and selection, and finally prototyping and development.

The final product of this thesis, EcoFlux, visualizes empirical models of molecular motion, photosynthesis, and respiration within the DoppelMarsh environment (Figure 2). Because these visualizations of carbon flow are driven by real-time sensor data, they change in correspondence with the live environmental conditions of the physical wetland. This project is the first of its kind to visualize molecular motion in 3D, in situ at the site, and driven by real-time data. EcoFlux is a tool to explore the invisible inner workings of ecosystems in a completely new way. These unseen ecological processes are vital to the health of an ecosystem and critical for our understanding of ecological restoration. DoppelMarsh and EcoFlux can be experienced in an immersive medium such as augmented or virtual reality to help visitors, scientists, and the local community understand the value of ecological restoration by experiencing the inner workings of the ecosystem.

Figure 2. The immersive experience of DoppelMarsh integrated with EcoFlux to demonstrate the unseen ecological processes like carbon flow that are integral to the health and restoration of an ecosystem.

This page is intentionally left blank

PROJECT BACKGROUND

UNDERSTANDING AND COMMUNICATING THE VALUE OF ECOLOGICAL RESTORATION

The practice of ecological restoration rehabilitates degraded, damaged, or destroyed ecosystems and is now an established response to biodiversity and habitat loss as the result of human activity. It is important to understand the value of ecological restoration for coastal, freshwater wetlands like Tidmarsh for two reasons: functioning wetlands provide many benefits to wildlife and neighboring communities, and degraded wetlands do not return to naturally functioning wetlands by themselves.

Functioning wetlands provide benefits for wildlife and human communities

Ecological restoration unlocks the many benefits that functioning ecosystems provide for wildlife and neighboring human communities, called ecosystem services. Ecosystem services are grouped into four categories: provisioning services, such as food and water; regulating services, such as the control of climate and disease; supporting services, such as nutrient cycles and crop pollination; and cultural services, such as spiritual and recreational benefits [6]. One of the primary benefits of ecosystem services is resilience to many of the environmental effects of climate change such as storm surges, hurricanes, and biodiversity loss [7].

A healthy, functioning wetland provides many benefits to the larger community, including carbon and nutrient cycling processes [8]. Due to the large amount of biomass, wetlands act as carbon sinks and can remove excess carbon dioxide from the atmosphere and produce oxygen instead. Wetlands are extremely important for denitrification, the processes by which excess nitrogen is taken up by plants and removed from the ecosystem [9]. Denitrification is a very important political topic in Cape Cod, where most of the homes have septic tanks instead of municipal sewer systems. Septic tanks leach nitrogen into the surrounding areas. In wetlands and waterways, this nitrogen can cause harmful algal blooms, setting off a chain of ecological responses that usually results in “dead zones” and a loss of local biodiversity.

Wetlands also provide important habitats for both aquatic and terrestrial wildlife. Wetlands are a key component of the amphibian life cycle; local species of frogs, toads, and salamanders need wetlands to lay eggs and raise aquatic offspring. Reptiles such as turtles also need freshwater habitats, and mammals like white-tailed deer browse on the shrubs that grow on the edges of the forest and the wetland. Water birds like great blue heron and snowy egret are common, but other apex predators like red-tailed hawks and sharp-shinned hawks rely on a more complex food web and will return to wetlands as biodiversity increases.

Coastal wetlands are rare and, in addition to all of the benefits of a functioning wetland, play a key role in the life cycle of many different species. For example, herring and other species of fish migrate upstream to freshwater wetlands to spawn. Herring are critical animals in the Atlantic food web because they connect primary producers, such as algae and zooplankton, to larger predators, such as striped bass and seals. In New England, herring help sustain ocean fisheries for more desirable species, such as bluefish and tuna, which ultimately support the larger marine food web and the entire coastal ecosystem. Coastal wetlands also provide habitats and supporting nutrition to migrating shorebirds. More than 50% of the original wetland for shorebirds has been destroyed or degraded since the late 1700s, causing decreases in populations of Eskimo curlews, buffbreasted sandpipers, whimbrels, and sanderlings, to name a few [10]. As a coastal wetland, Tidmarsh plays an important role in providing foraging and staging areas along these species' migratory routes.

Degraded wetlands do not return to functioning wetlands without human intervention

When cranberry farming was first established in Massachusetts, farmers built their cranberry bogs, such as Tidmarsh, in existing natural wetlands. Now that cranberry production has largely been outsourced to Wisconsin and Canada because of economies of scale, new plant species, and perhaps the effects of climate change, most Massachusetts cranberry farms are retiring. However, when cranberry farms cease production, instead of returning to their original wetland state, they transform into dry hills and forest. Although these forest ecosystems do provide benefits, natural wetlands are rare and provide key ecosystem services that common forest ecosystems cannot. Human intervention is necessary to prevent their succession to dry forest and return retired cranberry farms to beneficial, functioning wetlands.

The value of ecosystem restoration can be demonstrated through a system dynamics analysis (Figure 3). Climate change spurs a reinforcing loop of environmental degradation that decreases environmental health, which further decreases ecosystem services and ultimately, human wellbeing. However, the more resilient an ecosystem, the more it can withstand the deleterious effects of climate change and balance the effects of environmental degradation. This balancing loop of environmental resilience is activated when ecosystems recover and can perform various ecosystem services. The stock of cranberry bogs converts to a dry forest depending on the rate of natural succession, but can be converted back to a self-sustaining wetland if restoration efforts are applied. Once a bog becomes a dry forest, it cannot be converted back to a self-sustaining wetland barring massive physical transformation, long-term geological processes, or effects of other change in the area (e.g. water table or ocean-level rise). This system dynamics model demonstrates how restoration efforts are a key driver that supports ecological recovery and environmental resilience in the face of environmental degradation from climate change.

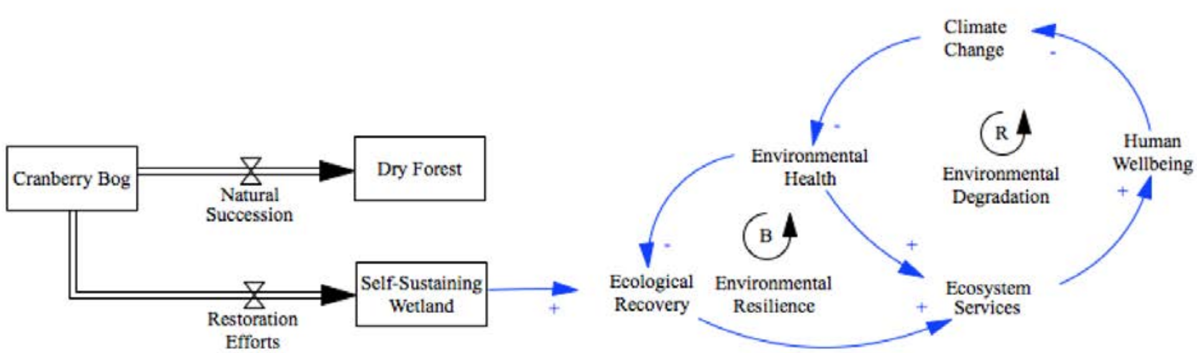

Figure 3. A system dynamics approach to environmental degradation, environmental resilience, and the value of ecological restoration at Tidmarsh. Restoration efforts can convert a cranberry bog to a self-sustaining wetland, which supports the balancing loop of environmental resilience.

Because ecological restoration is so valuable, it is imperative that we tell the story of Tidmarsh to demonstrate how ecological restoration of a wetland site provides value to the entire watershed as well as the local community in the form of ecosystem services. The direct effects of ecological restoration are often removed from our daily lives, so it is critical to communicate these positive benefits directly. Communicating these benefits raises awareness in the local community, which promotes a virtuous cycle of further funding and resources to support future restoration efforts. These additional causes and effects have been outlined in a system dynamics approach (Figure 4). This thesis focuses on the exogenous input of communication of ecosystem services as the main driver for the reinforcing loop of the value of ecological restoration, ultimately supporting the balancing loop of Environmental Resilience to help mitigate climate change. This model emphasizes that communicating the value of ecosystem services can be a key force in a larger system.

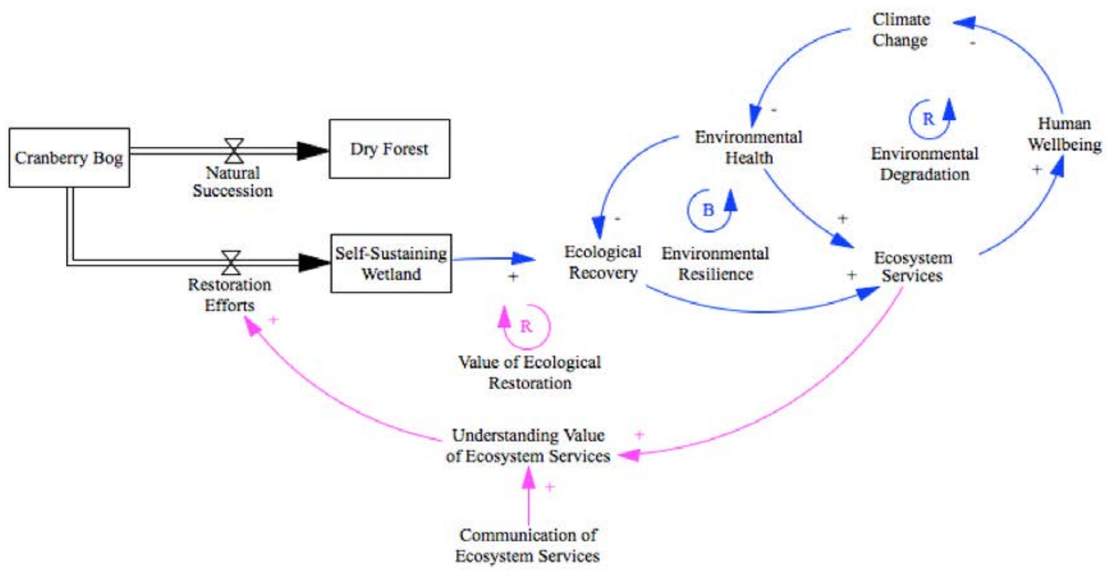

Figure 4. The addition of the exogenous factor communication of ecosystem services supports a new reinforcing loop of ecological restoration that enables the balancing loop of environmental resilience in response to the environmental degradation from climate change. The human-centered design process is used as a tool to understand how to best communicate ecosystem services in order to help all stakeholders understand the value of ecosystem services.

THE TIDMARSH FARMS RESTORATION PROJECT AND LIVING OBSERVATORY

Tidmarsh Farms is a 600-acre retired cranberry farm located in Plymouth, Massachusetts. The farm was originally built in the early 1900s and was in operation until 2010, when the current owner ceased farming and founded the Tidmarsh Farms Restoration Project to transition the decommissioned farm to a natural wetland system. As one of the few wetland systems so close to the coast of Cape Cod, Tidmarsh plays an important role in dynamics of the Eel River and Plymouth Harbor watersheds.

Tidmarsh will serve as a critical conservation site both as a buffer to rising sea levels and as a habitat for wildlife including amphibians, reptiles, mammals, and bird species such as snowy egrets, marsh wrens, and American bitterns.

The Tidmarsh Farms Restoration Project is part of an initiative called the Living Observatory [11]. The Living Observatory (LO) is a learning collaborative of scientists, artists, and wetland restoration practitioners. Its goal is to document, interpret, and reveal ecological change prior to, during, and following the Tidmarsh Farms Restoration Project, the largest freshwater wetland restoration project to date in Massachusetts (Figures 5 and 6). As a result of these efforts, the eastern section of Tidmarsh became a priority project for Massachusetts Department of Fish and Game's Division of Ecological Restoration (DER). The goal of the restoration project was to create a biologically and physically diverse, sustainable, freshwater wetland that enables wildlife to pass from the headwaters to the ocean. As of May 2017, Mass Audubon hopes to turn Tidmarsh East into a wildlife sanctuary [12].

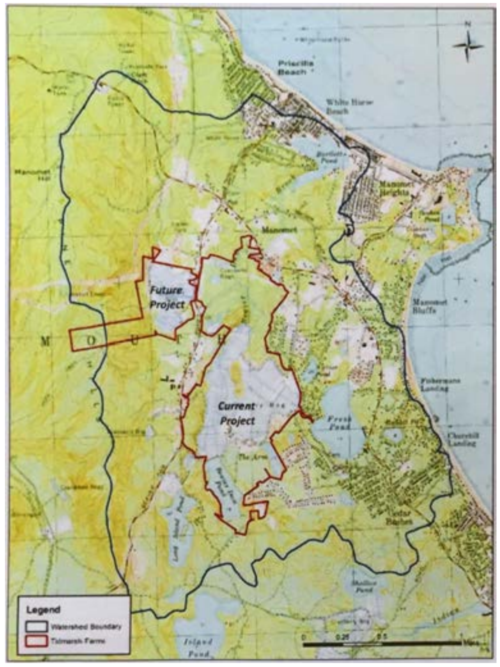

Figure 5. USGS map with overlay, courtesy Living Observatory Archive.

Figure 6. Google map with overlay, courtesy Living Observatory Archive.

Documenting Restoration Efforts and the Subsequent Ecological Change

In an effort to convert Tidmarsh to a healthy wetland, Living Observatory instituted large-scale restoration projects throughout the site (Figure 7). As a first step to restoring the natural processes of a self-sustaining wetland, stream channels were dug out to match historical records of the pre-cranberry bog water flow. Several ponds were carved out to provide a variety of habitats to wildlife and echo the original wetland. The peat mat was broken up and the topsoil was overturned, enabling growth from the dormant seed bank. Organic matter such as tree branches was added to the site to accelerate natural nutrient cycling processes. Through a specific plant program, native species were reintroduced to the area to support the return to a self-sustaining wetland.

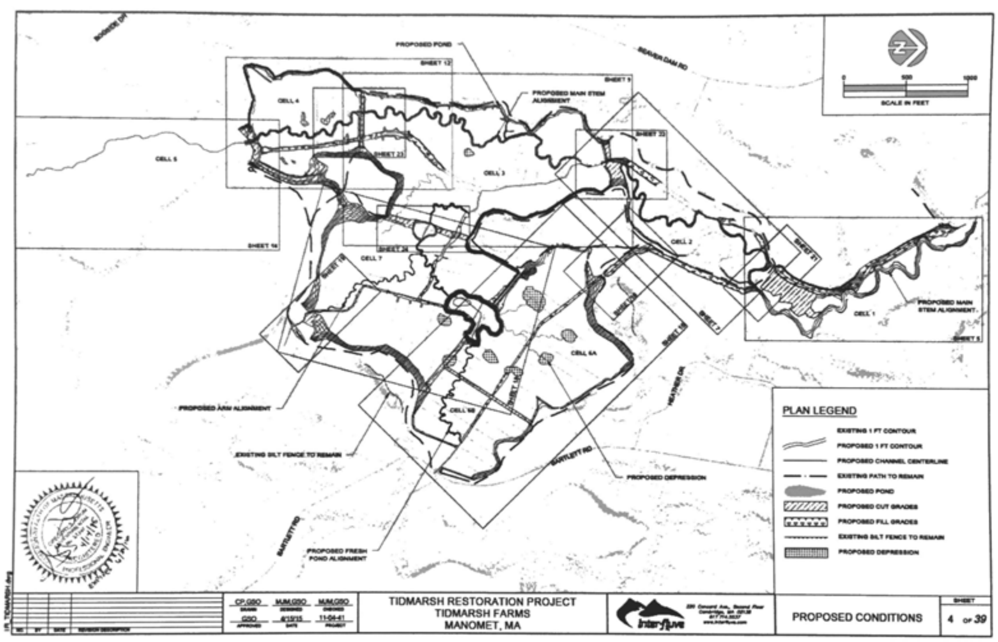

Figure 7. InterFluve, Inc. 100% Engineering Drawing, courtesy Living Observatory Archive.

The Tidmarsh restoration project represents a unique opportunity to document the post-restoration ecological change with environmental sensors and demonstrate the value of wetland restoration to the local community. This multi-sensory observation project provides valuable, never-been-seen data to support research and exploration into our understanding of hydrology, stream ecology, soil science, and other applications for environmental sensing. These data are made available to the entire LO group to enhance collaborative learning across disciplines. The mission of LO is to "tell the long-term story of the Tidmarsh Farms Wetland Restoration and to advance scientific knowledge and public understanding of wetland ecology." LO also provides the opportunity to teach effective strategies for reducing the impact of climate change, including minimizing environmental stressors such as invasive species and residential development, increasing habitat diversity, and connecting protected landscapes [13].

DoppelMarsh Project at the MIT Media Lab

The MIT Media Lab group Responsive Environments began collaborating with the Living Observatory and the Tidmarsh project in an effort to use technology to document the impact of freshwater ecological restoration. Responsive Environments designed and built a system of small, distributed, low-power sensors that measure the environmental conditions in the marsh, such as temperature, humidity, pressure, and illuminance. Microphones stream audio from the trees and underwater. These sensor networks help document ecological changes and allow people to experience the data at different spatial and temporal scales. For the first time, this sensor network enables visitors to experience an environment and its processes in a way that goes beyond the limitations of our human sensory inputs. This project is detailed here [14].

DoppelMarsh is the flagship project that integrates sensor data input with a digital version of Tidmarsh. It is a cross-reality sensory landscape constructed using the Unity game engine to experiment with presence and multimodal sensory experiences [15] [16]. DoppelMarsh enables visitors to experience and explore the Tidmarsh differently based on the real-time sensor data. For example, a visit to DoppelMarsh in the afternoon will be different from a visit to DoppelMarsh at midnight.

The sensor network at Tidmarsh forms a mesh network based on the IEEE 802.15.4 specifications. This network is built from approximately 100 low-power nodes, which contain a variety of sensors that monitor environmental parameters and which stream thousands of data points to a server twice per minute, 24 hours a day. These sensors were designed by Responsive Environments Research Assistant Brian Mayton so that additional environmental metrics (e.g. soil moisture) can be easily added in the future [17]. Data are relayed to a base station via a wireless mesh network and then uploaded to a remote server, where data are then streamed to the virtual environment via the ChainAPI server (Figure 8) [18]. The client is DoppelMarsh, an application built with Unity that can run locally on any machine.

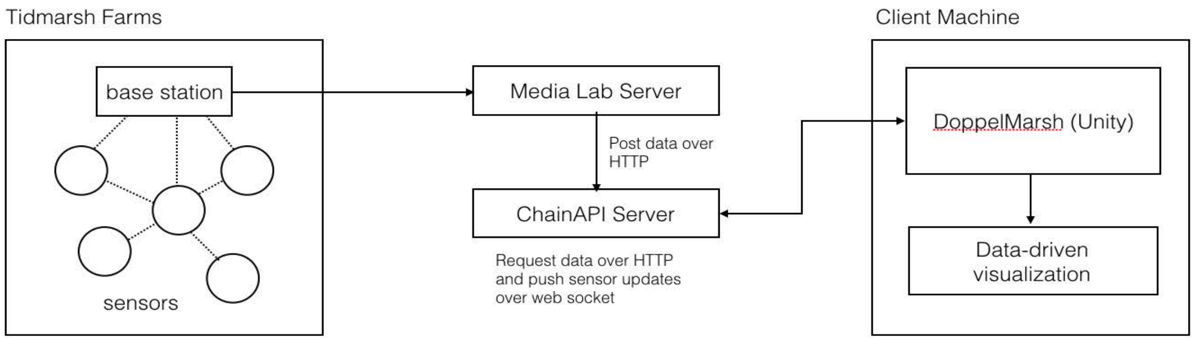

Figure 8. Data are collected via low-power sensor nodes, relayed to a base station via a wireless mesh network, and then uploaded to a remote server, where data are then streamed to the virtual DoppelMarsh environment via the ChainAPI server. These data are then used to drive models of carbon flow.

Several previous projects have explored different interface modalities to create novel experiences based in the real-time sensor network data. In 2013, the DoppelLab project created a new way to communicate sensor data by combining spatialized sonification with animated data visualization in a 3D virtual environment representing the MIT Media Lab itself [19]. In the DoppelLab environment, a visitor could explore both real-time and archived data remotely. DoppelLab was one of the first implementations of a cross-reality environment [20] and acted as inspiration for the future DoppelMarsh project.

Responsive Environments has continued to build functionality for DoppelMarsh to explore how additional information about the environment affects visitors' perception of "presence" at Tidmarsh. HearThere developed a spatial, auditory augmented reality that preserves the alignment between the virtual audio sources and the user's environment [21]. The SensorChimes project created a musical composition framework that facilitates novel musical mappings for the Tidmarsh sensors [22]. MarshVis is a data visualization website that graphically represents large influxes of data in a format that enables users to answer basic questions about the interdependent natural systems that support a marsh [23].

The sensor network provides new tools for monitoring and documenting as well as experiencing information in completely novel ways. These data enable us to explore the design and development of interfaces that mediate the limitations of human perception. As sensors become smaller and cheaper, they will become ubiquitous documentation tools of the modern world. It is important that we understand how to represent these data via interactive interfaces that humans can intuitively understand and experience.

PROJECT GOALS

The goal of this project is to develop a proof-of-concept technology that visualizes ecosystem processes to demonstrate the value of ecological restoration and can be used in future research to inspire curiosity for visitors, enhance scientific understanding for researchers at the Living Observatory site, and promote community development by demonstrating the value of ecological restoration.

In service to these goals, this thesis had four research objectives. The first was to identify the needs of potential visitors, the scientists conducting restoration research, and the Living Observatory community. The second was to learn how visualization in a three-dimensional landscape can be used as a tool for human understanding. The third was to develop experiments to determine new ways of how real-time, geographically specific data driving analytic models can be visualized in an augmented reality or virtual reality environment. And finally, the fourth objective was to build a proof-of-concept visual sensory experience that integrated with the existing DoppelMarsh project to serve as a foundation for future research.

The proof of concept was built using Unity, a game development engine currently being used to run the DoppelLab program. The visualizations integrate with the existing DoppelMarsh project to leverage real-time data and to create a seamless virtual experience. The project investigates how exploring changing ecosystem processes can help us understand the value of ecological restoration. This project supports the documentation of ecological change by remotely communicating these location-based, unseen processes.

AR / VR AS A NEW MEDIUM TO COMMUNICATE INFORMATION

IMMERSIVE EXPERIENCES: NEW OPPORTUNITIES IN AR / VR

Both augmented reality (AR) and virtual reality (VR) offer incredible promise as the next medium for immersive experiences. Augmented reality enables a viewer to experience a new layer of information on the existing world. When this augmented layer is truly integrated with the real world, this experience is called mixed reality. Virtual reality enables a viewer to physically stay in one location but experience completely different environments. These range from real to fantastical, from the top of the Empire State building to outer space to a completely new magical world. Simply put, VR helps you see a different world, while AR helps you see the world differently.

Due to their immersive and engaging nature, both AR and VR offer new opportunities to communicate information. Augmented reality is particularly compelling to help people connect to the environments they already know and believe they understand. It can illuminate layers of information that were previously inaccessible or provide new interfaces for interacting with digital objects as if they were physically present. This combination of novel visualizations and interactions represents a paradigm shift in the way that humans can experience the world.

MIXED REALITY AND CROSS REALITY

At the intersection of augmented reality and virtual reality lies mixed reality, which is the merging of both physical and digital worlds. In these new environments, physical and digital objects coexist and interact in real time. In mixed reality, digital objects can be treated as physical objects and are subject to all of the intuitive human interactions. Using this model, mixed reality can unlock new layers of potential interaction with the physical world based on the digital information.

In addition, this relationship between the real world and digital information works two ways. Digital worlds can also be built to reflect changes in the physical world—a cross reality. In 2009, Paradiso and Lifton defined cross reality as an extension of mixed reality but with an emphasis on ubiquitous sensor networks acting as the connection between the physical and digital worlds [24]. Both mixed and cross realities support new ways to understand and interact with the layers of our world.

DEVELOPMENT OPPORTUNITIES AND CHALLENGES FOR AR AND VR

Game Engines as a New Tool for AR / VR Research

One of the biggest advances for the AR / VR industry has been the availability of development-friendly game engines such as Unity. Research for AR / VR has lagged because of the daunting hardware requirements needed to thoroughly explore and experiment. Computer graphics research groups have traditionally depended on expensive, specialized graphics machines and displays, which put AR / VR research out of reach for all but the most dedicated research laboratories. However, with the explosion of the gaming industry and the mass market for computer games, even consumer hardware now has the horsepower to manage sophisticated interactive simulations and rendering engines and AR / VR displays are on the verge of ubiquity. As a result, scientific researchers can now utilize off-the-shelf game engines such as Unity to conduct experiments, deploy simulations, and visualize their work [25].

However, most research applications have utilized game engines for domain-specific simulations or games rather than as a new medium for communication or information visualization. Brown-Simmons et al. noted that using game engines for development removed cumbersome interfaces and enabled a shift in focus to the understanding of scientific processes [26]. Their planetary system game gave players the opportunity to explore scientific data to understand the full complexity of the solar system as an educational tool. Kot et al. were some of the first researchers to apply a game engine to information visualization, noting that it is critical to present the information as a metaphor in the form of physical entities so the paths of user interaction are clear [27].

Hardware Constraints for AR / VR Research

One of biggest limitations for implementing AR / VR technology in situations where they provide real value is the form factor of the existing hardware. Due to the computational requirements for rendering graphics in real time, most head-mounted hardware tends to be bulky and heavy. Unfortunately, this is an uncompromising tradeoff, as the bulk of the hardware is necessary to provide the high frame rate that creates a realistic, immersive experience and also prevents motion sickness in the viewer. The market has taken several different approaches to this problem for both AR and VR.

Most VR devices, such as the Oculus, HTC Vive, and Playstation VR, are tethered directly to large gaming computers, offloading the computation to enable lighter headsets and better performance. However, these headsets are also limited in their range of interactions as the user cannot move freely through space. Other VR devices such as Google Cardboard utilize the processing power in mobile phones to provide untethered but simple VR experiences. In these cases, a user must still remain in one location and can merely look around.

In addition to computation, there are more challenges for AR hardware. Some AR hardware is tethered to computers, such as the Meta 2, which still enables the user to view the world through the headset but which restricts his or her movement. However, the real value of AR is the ability to experience the world with an additional layer of synthetic information. To take advantage of this opportunity, most of today's AR headsets are untethered and enable the users to roam freely through the world, but at the expense of high-quality graphics and a wide field of view. The Microsoft Hololens takes this approach and contains a fully functional on-board computer that renders real-time graphics overlaying the existing world. It also contains a suite of sophisticated sensors that enables simultaneous localization and mapping (SLAM), the technology necessary to put holograms in 3D space rather than a simple visual overlay. With this technology, a holographic shoe on a table stays in the same place no matter where you move in a room. Google Glass takes a different approach, merely providing a heads-up display of visual information rather than a truly immersive augmented reality experience.

The work of this thesis was built to be hardware agnostic due to the tradeoffs for each type of hardware and the lack of resolution around a standard platform for either AR or VR. Ultimately, the vision for this project was that visualizations should be experienced directly on site at Tidmarsh so that the user experiences both the natural environment and unseen processes simultaneously. However, existing AR hardware limits the implementation of this vision because no AR hardware works well outdoors due to the wide-open spaces and variable lighting conditions. Therefore, this work was built to be experienced either on a personal computer or with a VR headset until the AR hardware can provide this experience.

Exploring Spatial UX: The Brave New World of Design in AR / VR

Because AR / VR is an emerging medium, there are few rules about its design and development, especially for user experience (UX). Existing design conventions have been structured for interactions with screens, not with 3D space. It is critical to rethink our design language so we can design spatial tools that enable users to intuitively interact with the experience. Users have fast learning curves when interfaces align with their mental model of the task they want to achieve. This principle manifested in skeuomorphism, a design trend made popular by the original iPhone in 2007, where the note-taking application was donated by a notepad icon, among others. Modern designers have replaced skeuomorphism in favor of more minimalist flat design for mobile and web development. However, with a completely new medium like AR / VR, skeuomorphism may return as a useful design tool to leverage user's experience in the physical world.

The designer who built one of the first Hololens applications proposed four best practices for AR user experience design: use interactions with physical objects as inspiration, 2D UX best practices do not apply to the 3D world, physical prototypes are helpful, and user interface elements do not have to be 3D [28]. Spatial user interfaces can leverage users' perception of volume and depth by placing digital objects, such as tools and content, directly in 3D space. There are still many unanswered questions about best practices when designing spatial user interfaces for AR / VR, especially because existing hardware platforms have their own native gestures and interaction mechanisms and there is no established industry standard.

THE VISUALIZATION OF INFORMATION

"The commonality between science and art is in trying to see profoundly - to develop strategies of seeing and showing."

- Edward Tufte

A FRAMEWORK FOR INFORMATION VISUALIZATION

As we collect more information about our lives, our movements, and our environment, we need new methods to explore and explain that information. Many technology companies today compete only on their dataset, relying on proprietary insights that enable them to build a better product and meet the needs of their customers. These datasets are often critical components of their decision-making process, and any tools that can help employees derive better insights and make better decisions are highly valuable [29].

According to theorist Richard Ackoff, there is a hierarchy from data to wisdom, where data becomes more useful as it is converted to information, then to knowledge, and then to wisdom [30]. In this model, data simply represents the discrete properties of objects and events, while information links elements together to provide meaning. Knowledge organizes and analyzes information to provide context. Wisdom is the most useful state because it applies those explanations and insights to future decision making. Visualizations for both data and information can be powerful tools for developing knowledge and wisdom. This thesis focuses specifically on visualizing information in the form of models driven by data, rather than the direct visualization of the data itself.

Fundamental cognitive psychology principles provide a foundation for information visualization best practices. The human brain is incredibly adept at finding patterns in information, especially when that information is presented visually. Edward Tufte is one of the modern thought leaders in information visualization design and his techniques help designers balance the saliency of the relevant goal and representing the completeness of the data set [31]. If a visualization is too abstracted, users may lose interest in the underlying mechanics. He identifies color as one of the strongest inputs for human visual memory and a critical tool for information visualization. Tufte stipulates that while powerful, color must be used sparingly and appropriately to articulate the key goals of the visualizations. Color can also provide multidimensional information by varying its inherently multidimensional quality: hue, saturation, and value. Color scales are a natural quantifier, especially for continuous, consecutive data, such as depth or height. Tufte also explores visualization techniques for representing narratives for space and time on “flatland” or 2D paper.

OFF THE PAGE: EXTRUDING INFORMATION VISUALIZATION INTO ANOTHER DIMENSION

Because there are no established design paradigms for AR / VR, it is not a surprise that information visualization in AR / VR is also a completely new frontier. Some of the techniques for 2D information and data visualization can be applied to spatial visualization, but in other ways, spatial visualization is an entirely new medium for multi-sensory storytelling. There are three components of spatial visualization in AR

/ VR: representing the information as an overlay on the real world, harnessing humans' spatial reasoning capabilities, and creating a data-driven experience.

Representing Information as an Overlay

Providing a visual overlay of information within an environmental context is useful in a variety of ways, including improving task performance and productivity. One study demonstrated that overlaying 3D instructions to explicitly demonstrate the execution of a procedure's steps reduced the error rate for an assembly task by 82%, particularly diminishing cumulative errors due to previous assembly mistakes [32]. Providing an AR information overlay during an assembly task also reduces the user's cognitive load and reduces the learning curve for novice assemblers [33]. With this in mind, the most interesting opportunities in spatial data visualization is combining immersive information overlays with real data streams.

Harnessing Spatial Reasoning Capabilities

With augmented reality, we can harness the capabilities of human spatial reasoning to understand data in new ways. Spatial reasoning is the ability to understand and manipulate objects in multiple dimensions: 2-dimensional, 3-dimensional, and 4-dimensional. With the ability to display information in a 3-dimensional space in context of the physical environment, AR creates new opportunities for our brain to quickly recognize patterns and make inferences in a way that might be impossible with a flat 2D visualization. However, most "3D visualizations" today merely extend into the z axis to convert a 2D graph to a 3D graph; they do not create visualizations that utilize 3D space to leverage humans' ability to find patterns in volumes and shapes. Better yet, spatial visualizations should represent abstract data as completely new environments or even as familiar objects, where a user can understand the data in an intuitive way that would not be experienced otherwise.

There are several examples where representing information in 3D space provides opportunities to recognize patterns. For example, in 2014, the National Air Traffic Services (NATS) in the UK produced a visualization of the flights coming in and out of Heathrow Airport on a typical day [34]. Their gorgeous visualization represented each flight as a motion path through 3D space. One of the most powerful moments in the visualization is when the audience realizes that it is possible to classify the different types of flight just by their motion paths. Commercial flights are smooth, general aviation flights are erratic, and military training flights are repetitive (Figure 9).

Figure 9. Stills from UK National Air Traffic Services visualization of flights at Heathrow airport on a typical day [35]. Three-dimensional motion path signatures clearly distinguish the different types of flights.

Artists and architects have been using these principles to construct sculptures and memorials for decades as a way to help their audiences understand scale. One example is the Holocaust Memorial to the Murdered Jews of Europe in Berlin, Germany (Figure 10). Although the memorial is open to interpretation, its vast sea of concrete slabs helps to elicit the full scale of the casualties in a way that visitors innately feel as that walk through the slabs. With AR, we can create digital, data-driven installations all around us.

Figure 10. Visitors appreciate the full scale of the deaths as they walk among the thousands of concrete slabs at the Memorial to the Murdered Jews of Europe in Berlin, Germany. This memorial is an example of how data can be spatially visualized to emphasize a characteristic of the information; in this case, the scale of the deaths. Image public domain.

"Data Visceralization": Creating a Data-Driven Experience

Humans are experts at living in the physical world, and AR / VR provides tools to visualize and interact with abstract information in a way that is intuitive and familiar. For example, most humans are adept at catching a ball from various distances at and various speeds. But what if we could experience the stock market, not as rows of numbers, but as a series of balls that we need to catch? Perhaps we would begin to recognize important patterns that would otherwise go unnoticed in a data table of stock prices. This example is a form of synesthesia, which is a neurological phenomenon where the stimulation of one cognitive pathways leads to an automatic response in another cognitive pathway.

There are many different ways that we can utilize humans' existing sensory pathways to provide information that is otherwise inaccessible in a form of "data visceralization" [36]. We are still beginning to understand how we might represent information in more holistic, natural ways to unlock new insights. Rather than exploring data in the form of 2D or 3D graphs, perhaps we can even leverage the organic data visualization that exists in nature, such as the rings of a tree or the movement of a flock of starlings (Figure 11).

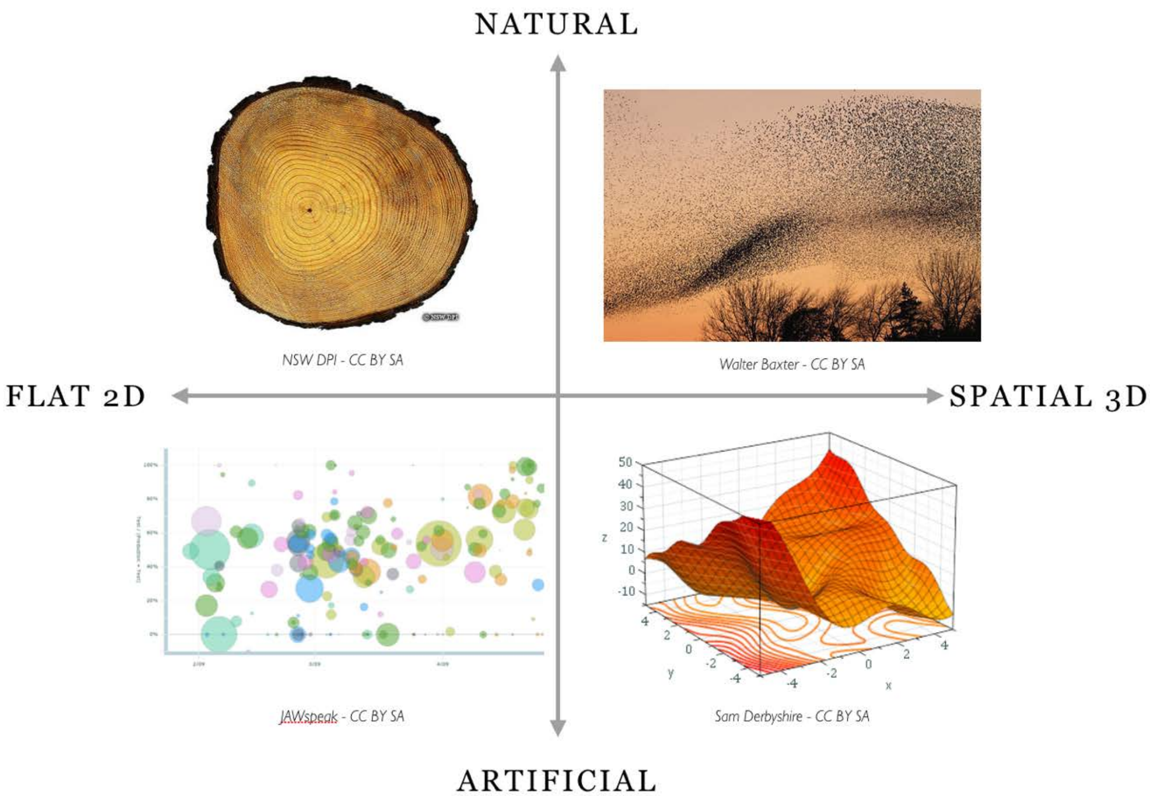

Figure 11. Visualization in 3D space is not restricted to a simple 3D graph; it can be an entirely new medium for processing information in a way that is natural and intuitive.

Human Factors Engineering for AR / VR Information Visualization

When designing experiences for AR / VR, there are several human factors that must be considered to provide the optimal experience. Although humans are exceptional at processing visual information and making sense of visual patterns, humans are also easily distracted by too much information. Visualizations in AR / VR must operate within the constraints of spatial user interfaces as well as the opportunities and challenges of a completely immersive medium.

The most limited resource when designing for AR / VR is human attention. Although humans can be extremely focused when their attention is engaged, there are intrinsic human attention biases. Humans are particularly sensitive to motion in our periphery due to the acuity in our rod photoreceptors located on the perimeter of our retina. Visual attention is extremely selective, so as designers, we need to minimize distractions and emphasize the important and relevant information. This can be a challenge given the limitations of current AR technology, such as the Microsoft Hololens, which has a limited field of view.

Therefore, during the design phase of this thesis project, it was important to consider how the movement of the visualization could convey important information without overwhelming the user. In this case, the visualizations use animations, rather than static graphics or icons, to add new levels of complexity to the design. The visualizations were also designed to blend seamlessly into the landscape at a distance and become more relevant and interesting as the user approached. There is still much to be learned about how humans interact and experience information visualization in AR / VR environments.

Curiosity and Interactive Experience Design

"I can live with doubt and uncertainty and not knowing. I don't feel frightened by not knowing things, by being lost in the mysterious universe without having any purpose."

- Richard Feynman

Unexpected tools for interaction design: curiosity and beauty

One goal of this project was to design an experience that inspired curiosity in its users by illuminating the beauty of natural processes. Curiosity is a powerful tool for designers, especially in the field of interaction design. Presenting the right information at the right time can intrigue users, which helps engage them with the visualization [37]. Once the users are engaged, specific interaction pathways can develop empathy for an abstract concept like ecological restoration.

In 1994, behavioral economist George Loewenstein proposed a new model for curiosity: The Information Gap Theory or "a form of cognitively induced deprivation that arises from the perception of a gap in knowledge or understanding" [38]. In other words, when we become aware of missing information, we become curious. This is the same drive that makes some people love puzzles and mystery novels. As part of his research, Loewenstein surveyed the existing scientific research focused on understanding curiosity's psychological underpinnings and dimensionality, which ultimately informed his Information Gap Theory of curiosity. Under this theory, curiosity exists when there is a gap between current knowledge and desired knowledge.

One key component of curiosity is its basis in our own understanding of a particular domain. For each person, the gap between what he or she currently knows and what he or she wants to know is different. Information gaps become more salient the more someone knows about a specific topic [39]. For example, someone who knows 8 out of a possible 10 things is more curious about the remaining 2 things than a person who only knows 2 out of 10 things. This principle supports a key component of interaction design—that each user's journey may be completely different, so information must be manageable so the user is not dissuaded from pursuing the final goal. Instead, the user can be encouraged and primed to engage by sharing key pieces of information at critical junctures in the user journey. Russell and Loewenstein confirmed that subjects were more curious when given parts of a greater whole, and that this curiosity resulted in more interaction with puzzles [40]. As our ability to design more personalized experiences increases with new forms of data, we can use these principles of curiosity to design high-quality interactive experiences.

Understanding and engaging curiosity can be beneficial in a number of ways, such as enhancing memory. Neuroscientists have begun to use brain scanning technology (e.g. fMRI) to uncover correlations between intangible curiosity and specific neurological benefits. For example, it has been shown that curiosity increases activity in memory areas in the brain when subjects are tested, suggesting that curiosity may enhance memory for surprising new information [41]. If curiosity increases memory, then it can be leveraged to create better environments for learning and communication.

The cognitive mechanisms that support curiosity are similar to those that support the appreciation of beauty, and its behavioral mechanisms can be harnessed in the same way to create engagement. Ishizu and Zeki propose a brain-based theory of beauty: specific areas of the brain can be activated by multiple modalities, such as visual and musical sources [42]. Others hypothesize that beauty is deliberate incompleteness—similar to the Information Gap Theory of curiosity—such as when a viewer wants to see more but cannot explain why [43]. Whether beauty relies on the same neural mechanisms as curiosity, leveraging either one has a benefit in product design.

This page is intentionally left blank

Human-Centered Design Research and Analysis

"So that when I look up at the night sky and I know that yes, we are part of this universe, we are in the universe, but perhaps more important than both of those facts, is that universe is in us."

- *Neil DeGrasse Tyson*

The Value and Process of Human-Centered Design

This thesis takes a human-centered design approach to uncover the existing human needs that drive a community's understanding of the environment, wetlands, and ecological restoration. Human-centered design is a creative approach to solving problems by building on participatory action research, which includes observing the problem within context, brainstorming, conceptualizing, developing, and implementing the solution.

Human-centered design is a method of product design and development built on a foundation of "design thinking," a term coined by David Kelley in 1991 when he founded the design consultancy IDEO. Design thinking promotes creative strategies to solve users' problems. The goal of human-centered design is threefold: develop a product that is desirable to the user, feasible giving existing technology, and viable as a business. This process usually creates products and interfaces that are more intuitive, easier to learn, and are more successful in the market. Good human-centered design has even been shown to minimize cognitive load when using products, enabling users to focus on the task at hand [44].

Human-centered design methods are part of the canonical product design and development process articulated by Ulrich and Eppinger in their book, *Product Design and Development, 6th Edition* (Figure 12) [45]. In this model, each phase of the process is sequential and tightly coupled, with rigorous testing to identify and manage uncertainties. This is an exceptional process for physical product design, where design for manufacturing and production are as important as the initial concept development and system design phases.

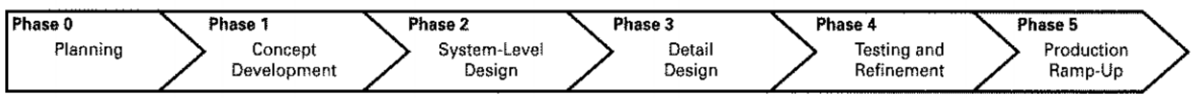

Figure 12. The product design and development process from Ulrich and Eppinger's canonical Product Design and Development, 6th Edition text.

In digital design, the stages of the process are less focused on the production and manufacturing design and more focused on the phases of digital prototyping, development, and implementation. In this thesis, there is an emphasis on the user research phase as a method to uncover the cognitive and behavioral levers that define how a community values ecological restoration. As a result, the design process was divided into eight key phases (Figure 13). In line with the goal of demonstrating the value of ecological restoration, it was first important to understand the stakeholder ecosystem for Tidmarsh as well as the underlying motives, goals, and values of those stakeholders. Key insights from the active learning and stakeholder research phase informed concept selection and feature prioritization for the final product.

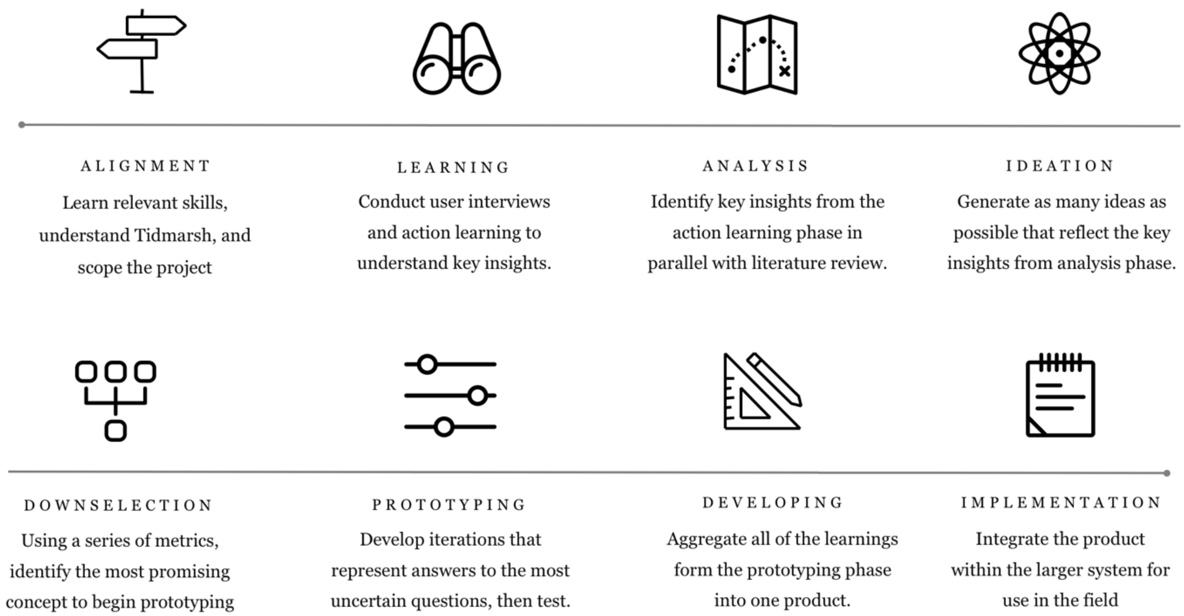

Figure 13. The process used for this thesis with an emphasis on learnings from the user research phase to design and develop a digital product.

Although business viability is an important component of any product design and development process, this thesis focuses on building a foundation for a communication and exploration platform. Good communication increases the public's understanding of ecosystem services, which will have long-term economic value for the community. In line with the system dynamics analysis, promoting the community's understanding of the financial, health, and other benefits of a healthy, self-sustaining wetland will support a virtuous cycle of ecological restoration and resilience.

ALIGNMENT AND LEARNING: USER RESEARCH

The first two phases of this thesis focused on understanding the larger goals of the Tidmarsh restoration project as well as individual stakeholders and potential future users, such as Mass Audubon site visitors. Because Learning Observatory is a consortium of research scientists, each overseeing their own projects with their own goals, it was important to understand individual objectives as well as the larger mission. The user research process included five site visits to Tidmarsh, two semi-annual Living Observatory meetings, two visits to individual research labs, four in-depth interviews with leaders of the Tidmarsh project, and four in-depth interviews with experts in information communication, education, conservation, and science visualization (Table 1).

As a critical step in the human-centered design process, in-depth interviews provide a level of qualitative data that other forms of assessment, such as surveys, rarely capture. The purpose of the in-depth interviews is to explore and uncover latent needs, or problems that those users do not realize they have. Seven is the preferred number of interviews that supports that maximum number of insights before diminishing returns on time spent interviewing, [46] though it is also important to capture a range of users. In-depth interviews lasted approximately 1-2 hours and were voice or video recorded. Each of the user's statements can be interpreted as a data point to support key insights.

NAME	TITLE	KEY QUOTE	KEY INSIGHTS
Glorianna Davenport	Tidmarsh Board of Directors	*"Humans can't relate to ecosystem processes because they can't see them or the processes are operating on a different time scale."*	• Relating to an ecosystem • Representing time across scales • Understanding larger processes
Alex Hackman	Tidmarsh Site Manager	*"Experiencing for me can also mean being quiet. Listening and looking and smelling and having a sensory experience that is not as human. "*	• Separation from human self • Unseen & unknown • Innate value in nature
Jessica Norriss	Urban and Environmental Policy and Planning, Tidmarsh Advisory	*"It's not just about what we value in terms of money, but how we can measure other types of value."*	• Balance between decision makers • Ecosystems are complicated

	Council		• Communicating value
Kate Ballantine	Tidmarsh Board of Directors, Assistant Professor at Mount Holyoke College	*"I would love to see below the ground and hear decay in a log."*	• Microcosm of activity • Experience in situ • Hear what you can't see
Alex Duckles	Expert in science documentaries and storytelling	*"You might have more calls to action or you can reframe your focus on what is really important in the world."*	• Goal-driven communication • Large-scale habitat loss • Deliberate focus
Shannon May	Expert in science education	*"I really love the not knowing. Seeing things change over time really piques my curiosity—I'm fascinated with things changing over time."*	• Breaking the fourth wall • Naming for social connection • Finding the circle of life
William Remsen	Expert in cultural heritage preservation and conservation	*"Nature transcends the immediate. It can be intellectual or spiritual. It allows us to be amazed."*	• Nature is transcendent • Humans as part of nature • Access to ask questions
Gael McGill	Expert in science visualization	*"Molecules don't 'decide' where to go. Everything we see is governed by very simple chemical rules, repeating over and over."*	• Basis of molecular motion • Visual literacy • Adaptive learning

Table 1. As part of the alignment and learning phase, eight in-depth interviews were conducted with a variety of stakeholders, including Tidmarsh leadership and subject matter experts.

Analysis: Understanding User Needs

After the extensive research phase, there were several key findings about the needs of the stakeholders. These findings describe the underlying emotional needs that people have when interacting with nature that can be used to inform the ultimate product design (Table 2).

KEY FINDINGS	DETAIL
INEXPLICABLE EXPLORING	Humans love being in nature, but no one understands why. Humans need the time and space to explore.
SOCIAL OWNERSHIP	Curiosity is part of survival, and naming the things you see can be a social bonding experience with others.
CREATURE CHARACTERS	Humans love watching animals because we can create stories that take place before and after the moment.
CONNECTED PRESENCE	Nature reminds us of our own insignificance within natural cycles and processes, such as death and decay.

Table 2. Four key themes emerged as the result of the analysis from the in-depth interviews.

1. **Inexplicable Exploring**

   Humans love exploring and understanding the world around them. This tendency may be based in our evolutionary past; it was important to know, and therefore avoid, the location of the saber-toothed tiger den. Humans also needed to forage for food, water, and shelter. In most conversations, the interviewed experts could not articulate why they enjoy nature and exploring so much. Some people had a reverent appreciation for the wanderlust of climbing mountains, finding hidden waterfalls, and quietly observing the stillness of a glacial lake. In these scenarios, these places and moments belong to them.

2. **Social Ownership**

   Naming has power. If you can talk about something, such as a physical object or an idea, then you can own it. You can share it with other people as a social bonding experience and begin to ask questions about it. Once you can name your experience, you can ask questions and search for more answers. Sharing our experiences helps humans provide context in both time and space. Since most natural processes happen on a time or space scale that is not intuitive to humans, our ability to describe these phenomena is critical to understanding of them. However, we can only share what we can perceive through sight, sound, or other senses.

3. **Creature Characters**

   Everyone loves animals. They become the characters in the stories about our visits to forests, wetlands, and mountains. They are entertaining and captivating, and unlike animals on TV, animals in real life are ephemeral. If you move, you might startle them. Animals in the wild break the fourth wall: the see-er is also the seen. One theory is that humans love creatures in nature because of our ability to project theory of mind. If we see a turtle at pond, we imagine the story of the turtle: where it was before we saw it, how it lives its life, and what it will do when we leave the pond. Humans easily develop empathy for animals and sometimes for plants, especially if we can directly bond with them through taming. However, these connections usually focus on individual organisms and do not extend to the entire ecological system.

4. **Connected Presence**

   Humans can feel disconnected from their "humanness" when surrounded by nature, especially because our sense of humanness is often constructed from our daily interactions with other humans. For some people, this disconnection can be very uncomfortable, but for others, it can be an almost reverent or spiritual experience. Nature reminds humans of our insignificance within the scale of time and space in the universe. There are repeating, dynamic patterns that are out of our control. Nature is impermanent, and it shows us the cycles of death and decay and reminds us of our part in it, which can be invigorating to some people and daunting to others. We connect to nature each in our own way and feel our place, both separate in our humanness and innately connected in our own wildness.

These four key findings (inexplicable exploring, social ownership, creature characters, and connected presence) support the next phase of the design and development process: developing a needs list. A needs list is an opportunity to convert key insights about human behavior into characteristics of the final product that address those needs (Table 4). Although the needs list is primarily derived from the in-depth interviews, additional research on curiosity, beauty, and their influence on the field of interaction design have also informed the needs list (Table 5). Once these needs had been identified, they were prioritized based on desirability, feasibility, or viability. This strategic prioritization enabled a focused list of product specifications that defined the direction of the prototyping and development phase.

USER RESEARCH NEEDS LIST

Key Theme	**Need 1**	**Need 2**
INEXPLICABLE EXPLORING	Experience encourages humans' interest in finding "secret" places.	Experience is self-paced to enable people to make their own way in time and space.
SOCIAL OWNERSHIP	Experience provides opportunities for people to name their experiences so they can share it with others.	Experience creates a new way of seeing the world that people can take with them to other locations and areas.
CREATURE CHARACTERS	Experience creates the same "theory of mind," story-building mindset that people experience when they see animals.	Experience provides the same emotional connection to the larger ecosystem as humans usually get with animals.
CONNECTED PRESENCE	Experience emphasizes processes that occur on a scale (time & space) larger than humans usually inhabit.	Experience helps people feel connected and present (both seeing & seen) to the beauty of a natural environment.

Table. 3. Development specifications resulting from the in-depth interviews as part of the user research phase

LITERATURE REVIEW NEEDS LIST

Key Themes	Need 1	Need 2
INFORMATION GAP THEORY	Experience connects to something that humans already know or are familiar with.	Experience is not a complete answer; it is part of an unexplained mystery.
CURIOSITY & MEMORY	Experience reveals information that is “surprising” and causes people to search out more information.	Experience creates one or several key takeaways that people will remember, especially in other environments.
RESOLUTION & RELEVANCE	Experience represents a part of a greater whole—a piece of the puzzle, not the entire picture.	Experience focuses in a domain where most people already have some knowledge and then builds upon it.
FINDING BEAUTY	Experience creates an emotional connection that holds our attention.	Experience hints at a larger pattern and is incomplete; it prompts people to search for what is missing.

Table 4. Development specifications resulting from key themes in literature review on curiosity, memory, relevance, and beauty.

IDEATION & CONCEPT SELECTION

"There's a crack in everything – that's how the light gets in."
—Leonard Cohen

CONCEPT GENERATION

With the guidelines provided by Ulrich and Eppinger [47] as well as lateral thinking techniques from design thinking, the next phase of concept generation provided an opportunity to explore potential solutions to the established problems. In this initial brainstorming phase, the emphasis is on quantity over quality. As part of the process, over thirty concepts were sketched on Post-It notes. Post-It notes are a very useful tool at this phase because they enable quick organization and grouping, which sometimes leads to more ideas. Although this process is often done as part a creative exercise with a team of people, it can also be used independently. In this stage, wild ideas are encouraged; even if the wild ideas are not feasible, components of these creative ideas can often be incorporated into the final solution.

After sketching, concepts were grouped into three major categories: movement of water, movement of carbon, and the mycorrhizal network (Figure 14). Each of these concepts is integral to the ecosystem services capabilities of Tidmarsh. Because Tidmarsh is a freshwater wetland, the movement of water is particularly salient because it moves through the streams and ponds as well as through trees via the process of transpiration. Wetlands act as important carbon sinks [48], so visualizing how carbon dioxide is moving in or out of the marsh would help convey the importance of ecological restoration. And finally, trees and plants communicate via underground networks of mycorrhizal fungi, even sharing vital nutrients and carbon in times of need [49] [50]. Very little is understood about this "wood-wide web," but several studies have proposed its importance to the health of an ecosystem [51] [52]. One study even found evidence that trees were warning neighboring trees of an incoming aphid attack via this network [53]. Visualizing this communication network would advance both the scientific study of these mycorrhizal networks and provide insight into the complex and unseen processes that drive ecosystems. Each of the three concepts would provide value in line with the goal of the thesis, so each concept was evaluated to determine the final direction.

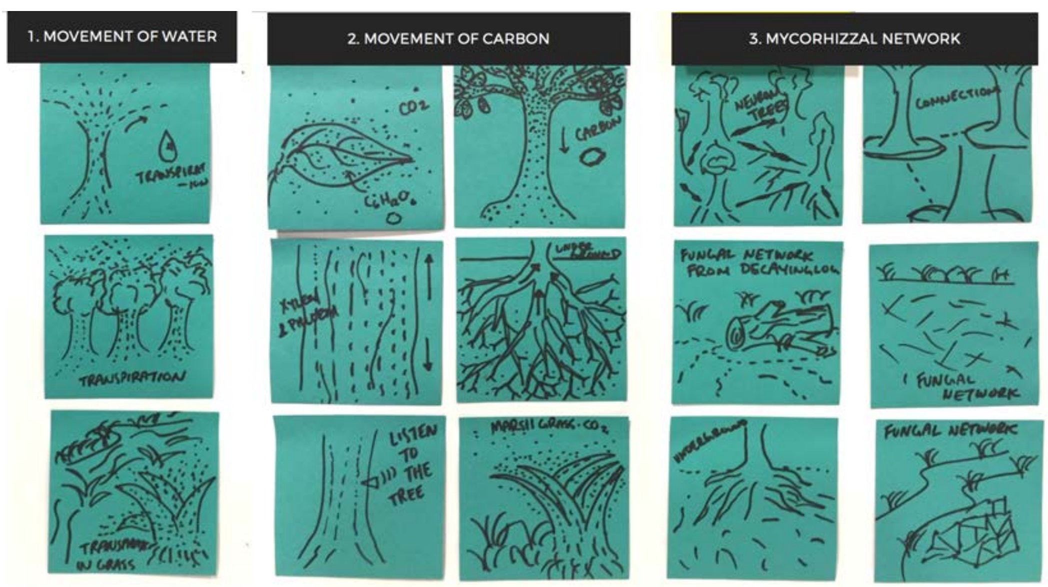

Figure 14. Brainstorming and then grouping in major concept groups on Post-It notes

Concept Selection

After three major concepts were identified in the concept generation phase, the next phase was concept selection. This selection process was based on the opportunities and challenges for each concept as well as scoring of desirability, feasibility, and viability for each concept. The desirability reflects a user's willingness to use the product. Feasibility reflects the technical complexity based on the tools and timeline available. In parallel to the user interviews and site visits, several different tests were conducted within Unity to determine the feasibility of the final product (Figure 15). In this process, the viability of the concept was assessed on how well the concept fit into the goals and larger vision of the Tidmarsh project.

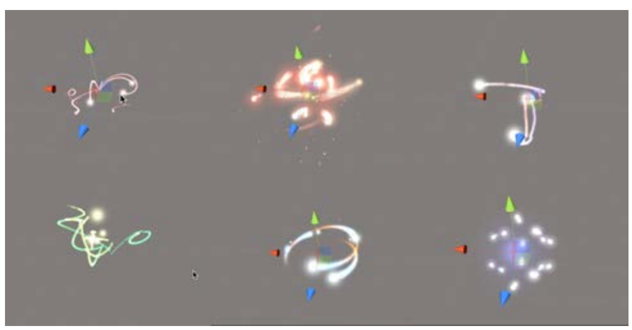

Figure 15. Early experiments with simple Unity particle systems to test the capabilities and visualization styles.

Using this framework, the movement of carbon was determined to be the most desirable, feasible, and viable (Table 5). There are numerous opportunities within the movement of carbon to emphasize direct effects of ecosystem services, such as demonstrating that a restored wetland acts as a carbon sink, reducing the rate of climate change. It captures many of the same processes as the movement of water but also lays the foundation for more complex visualizations, such as subterranean communication between plants via the mycorrhizal network. There are also several existing models for both photosynthesis and respiration, the processes that govern carbon flow, which could be used to drive visualizations in real time. Rates of photosynthesis and respiration have also been shown to influence nitrogen removal in wetlands [54], which is a critical ecosystem process and further demonstrates the value of ecological restoration. One of the biggest reasons to visualize the movement of carbon was that very few static and virtually no dynamic visualizations exist of this process despite its value within an ecosystem. Visualizing the movement of carbon also has fewer implementation challenges than the other concepts.

Although both the movement of water and the mycorrhizal network concepts were very interesting, both had insurmountable challenges. The flow of water through an ecosystem has few standard models and the interaction between groundwater, streamflow, and transpiration may be more complicated than previously thought, [55] posing more problems for an accurate visualization. Mycorrhizal networks were particularly intriguing, but there is so little scientific research about the communication processes that there was no way to represent the data being collected by the Tidmarsh sensor network with a visualization. It is important to keep in mind that visualizing poorly understood models or unrelated data can lead to false beliefs. Due to the natural role of uncertainty in science, we can rarely model phenomena with complete confidence, but we need to be mindful of introducing new misconceptions. In the case of the mycorrhizal networks, any visualizations would be pure conjecture and might create more mistaken beliefs than useful insights. Since visualizations are more powerful when they can build new experiences with real data, visualizing transpiration or mycorrhizal networks were not viable options.

MOVEMENT OF WATER	MOVEMENT OF CARBON	MYCORRHIZAL NETWORK
Opportunities Visualization would be powerful to see how all the vegetation and bodies of water are connected (works well with a wetland). Transpiration calculations are easily integrated with real-time data collection. Water is a great character that connects all the different processes in a wetland.	***Opportunities*** Emphasizes part of the respiration and photosynthesis of plants that is not otherwise seen or thought about. Integrates with time of day and real-time data collection. Demonstrates the similarities and connection between organisms.	***Opportunities*** Experience would be stunning—-visually, intellectually, and emotionally. There are no existing visualizations so it would be ground-breaking science. Would take advantage of augmented reality technology as a subterranean visualization. Emphasizes the connection between trees as one living organism and to build empathy.
Challenges Water is not a method of communication, so it is not as strong an emotional connection. Does not convey the holistic system within a larger ecosystem.	***Challenges*** Most interesting part of visualization carbon is the subterranean sharing, which could be visualized via the mycorrhizal network.	***Challenges*** Unclear if there are mycorrhizal networks in wetlands (though there probably are). More focused on trees and forests than wetlands.
Desirability: ● ● ● ○ ○ ***Feasibility:*** ● ● ● ● ○ ***Viability:*** ● ● ● ○ ○	***Desirability:*** ● ● ● ● ● ***Feasibility:*** ● ● ● ● ○ ***Viability:*** ● ● ● ● ○	***Desirability:*** ● ● ● ● ● ***Feasibility:*** ● ● ○ ○ ○ ***Viability:*** ● ● ● ● ●

Table 5. Concept Down-Selection based on the balance of opportunities and challenges as well as the scoring of desirability, feasibility, and viability for each concept.

PROTOTYPING IN UNITY

Prototyping is one of the most critical steps of the product design and development process. It enables the designer to test uncertainties that will ultimately decide whether the product succeeds or fails. Prototyping in the digital space has the same principles as prototyping for any physical product: fail early, fail often, and learn from your mistakes.

For this thesis, the prototyping process primarily involved Unity. It was important to understand the capabilities and constraints of the existing technical assets and evaluate any remaining uncertainties in the development process. One of the first experiments was to understand how the native Shuriken particle system in Unity could be used to visualize flow within a system, either independently or with scripted mathematical modeling (Figures 16 and 17). One of the largest uncertainties was the technical integration of visualizations with the existing DoppelMarsh project and its real-time data streams, so this capability was tested early on in the process. Each of these experiments helped to de-risk any remaining uncertainties that might have derailed the project.

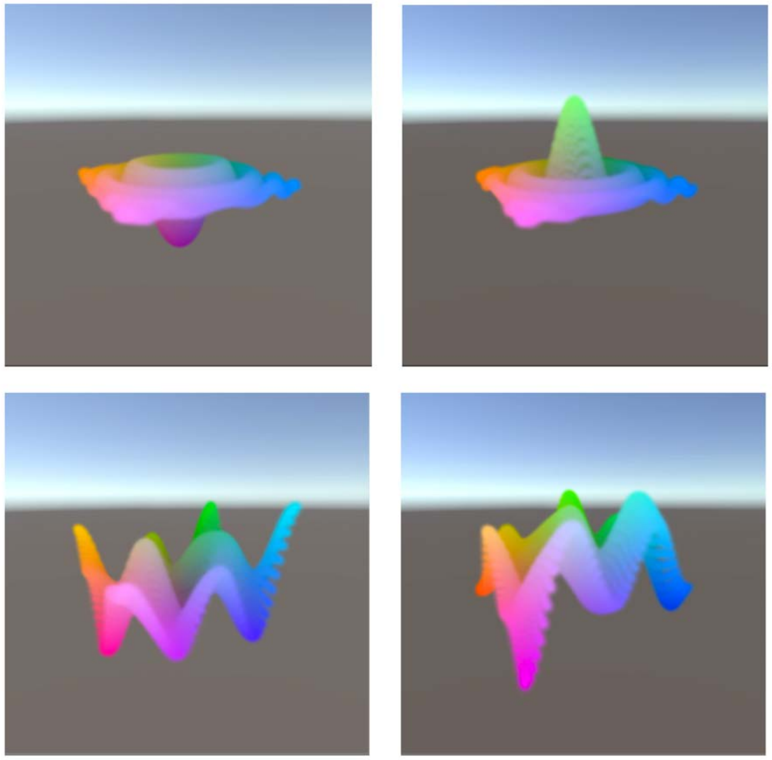

Figure 16. Early experiments with mathematical models and animation (2D and 3D sine waves) using Unity particle systems

Figure 17. An early test to automatically generate a particle system at the site of each sensor node when the node subscribes and then update when the data changes.

This page is intentionally left blank

ECOFLUX: VISUALIZING UNDERLYING DYNAMICS IN MOLECULAR MOTION

"Any sufficiently advanced technology is indistinguishable from magic."
- Arthur C. Clarke

MOLECULAR MOTION AS A FOUNDATION FOR ECOSYSTEM PROCESSES

Biology, chemistry, and physics are each governed by rules of molecules. They are the key to the connection between structure and function—or between environment and process. Modeling these molecular processes provides a foundation for understanding all other processes—first chemical processes, and ultimately ecosystem processes (Figure 18).

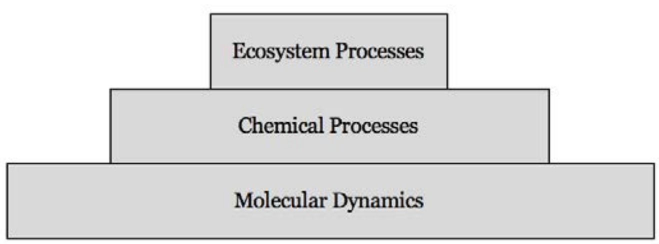

Figure 18. Molecular dynamics provides a foundation for all other chemical processes, which in turn support the ecosystem processes that govern ecosystems.

As a first step to visualizing carbon flow in the context of real-time environmental conditions, it was necessary to understand how carbon molecules behave as part of the carbon cycle. The motion of molecules is important to the understanding of many critically important concepts in biology, chemistry and physics. At its core, temperature is simply the motion of molecules with a given amount of kinetic energy. Molecules at a lower temperature move slowly, while molecules at a higher temperature move more quickly. This principle is connected to different states of matter and is why water turns to ice when it cools (molecules are moving very slowly, creating a lattice structure) and evaporates into a gas when it heats (molecules are moving very quickly).

Existing models and visualizations of molecular motion have focused primarily on simple 2D visualizations with no external input. The majority of these visualizations demonstrate a molecule in isolation or a static system. However, dynamic visualizations are much more powerful tools for communicating structure-function relationships [56]. Some complex simulations enable learning by providing interactive features, such as temperature sliders.

This project visualizes molecular motion in 3D, in situ at the site, and driven by real-time data. Molecular motion is usually abstracted from its real environment, but this project takes a different approach and aims to visualize these unseen, abstract processes within a familiar, relevant environment. This visualization also helps an audience connect to a process that occurs on a time and space scale that is both faster and smaller than our own.

EXISTING MODELS FOR MOLECULAR MOTION

The interactions between molecules can be added to calculate the total potential energy of a molecular system:

$$U = V_{LJ} + V_{EL} + V_{BS} + V_{AB} + V_{PT} + V_{IT}$$

Where:

- V_{LJ} is the Lennard-Jones potential (Van der Waals attraction and Pauli repulsion)
- V_{EL} is the electrostatic potential energy according to Coulomb's Law
- V_{BS} is the bond-stretching energy for covalent bonds
- V_{AB} are the angle-bending energy
- V_{PT} and V_{IT} are the proper and improper torsional energies

Once the interactions among atoms are defined, the position, velocity and acceleration of each atom are calculated using a numerical method (e.g. the Verlet method or the Runge-Kutta method) to solve Newton's equations of motion according to the forces derived from the gradients of the interaction potentials involving the atom [57]:

$$m_i \ddot{R}_i = -\nabla_i U(R_1, R_2, ..., R_n)$$

Where Ri is the position vector of the *i*-th atom and m_i is its mass.

Computation intensity scales with the number of molecules

However, there are challenges to visualizing complex molecular dynamics in a three-dimensional environment. Accurate visualizations are a trade-off with computational intensity. Due to their simple graphical nature, 2D visualizations can afford more sophisticated computations to calculate individual molecule velocities based on collisions and intermolecular forces, such as Van der Waals, while retaining their quality and performance. Unfortunately, early experiments to reproduce simple calculations of these intermolecular interactions in a complex 3D environment were extremely computationally expensive, resulting in slow and uninteresting visualizations (Figure 19).

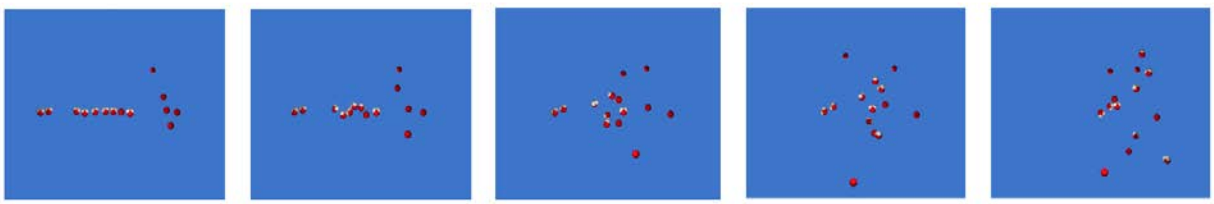

Figure 19. An attempt to model molecular dynamics based on Unity's CellUnity project. Unfortunately, due to the computations required to compute the intermolecular interactions of each individual molecule, the simulation could only be run with a limited number of molecules. This experiment yielded slow and uninteresting results.

One of the key learnings from this stage of prototyping was the discovery that computation would be a limiting factor in the final visualization. Models that can easily be visualized with only a few molecules do not scale when the number of molecules increases. Performance is even more of a constraint when viewing visualizations using AR or VR hardware, where slow calculations can result in a reduction in frame rate and a large drop in the quality of the experience. As a result, it was important to think about the problem differently.

CHEAP COMPUTATION: CALCULATING THE PROBABLE VELOCITIES OF GAS MOLECULES WITHIN A SYSTEM

For visualizing the molecular motion of carbon flow in an ecosystem, it is possible to visualize how a *system* of carbon molecules behaves, rather than calculating individual intermolecular interactions. In the carbon cycle, carbon has many forms. Carbon exists as complex molecules in all organic matter, but also as carbon dioxide or methane in the air and carbonic acid in water. Carbon molecules in the form of carbon dioxide are governed by environmental factors, such as temperature, wind, and humidity. Because carbon dioxide in the atmosphere can be modeled as a simple diatomic gas, there are cheaper computation methods that can be applied to the entire system.

When particles of carbon dioxide exist as a gas system, they can be described by a number of gas laws including the Kinetic Theory of Gases [58]. This law explains the behavior of a gas formed from particles that rapidly and continuously collide with each other. According to this theory, the temperature of a gas is a measure of its average kinetic energy, and kinetic energy of a particle is related to its velocity according to the following equation:

$$KE = \frac{1}{2}mv^2$$

where KE represents kinetic energy of a particle, m equals mass, and v^2 is the square of its velocity. Therefore, the temperature of the system can also be described as the average kinetic energy of its particles. Although the diffusion equation can also be used to describe the behavior of the collective motion of particles in a system, it is independent of temperature and therefore less useful when integrating the real-time data from Tidmarsh.

Several properties can be derived from the Kinetic Theory of Gases, including Boyle's Law, Charles' Law, Gay-Lussac's Law, and ultimately the Maxwell-Boltzmann probability distribution. The Maxwell-Boltzmann distribution is used to describe particle speeds in a system of idealized gases with only brief collisions to exchange thermal energy (Figure 20). A particle speed probability distribution indicates which speeds are likely given the temperature of system and the mass of the particle. In this model, collisions are irrelevant because while they affect the individual speeds of the molecules, the distribution of speeds across particles remains the same.

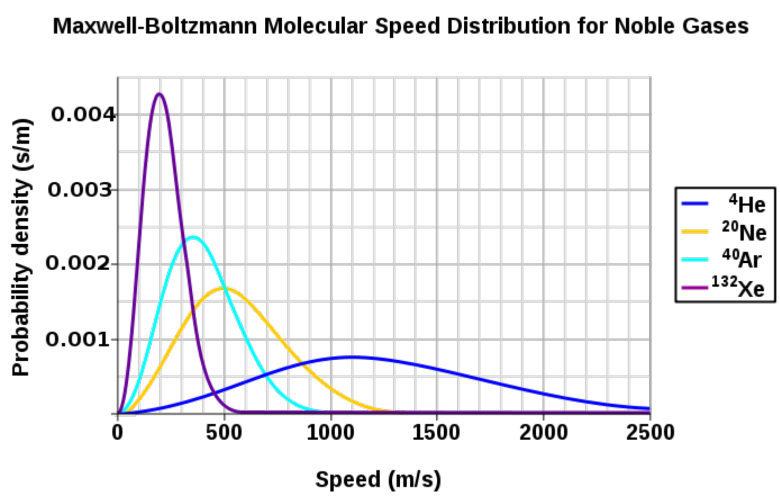

Figure 20. This Maxwell-Boltzmann distribution demonstrates the probability of speeds for any particle within a system at a constant temperature. Probability distributions vary by molecular weight of the gasses and by temperature. This example demonstrates the Maxwell-Boltzmann distribution for several noble gases at 298.15 K (25 °C). Image public domain.

The Maxwell-Boltzmann distribution can be used to calculate properties of particles in an entire system, which is particularly useful for efficient computation when developing a visualization. For a particle in the system, the Maxwell-Boltzmann distribution can be used to predict the probable speed v_p, the average speed v_{ave}, and the root-mean-square speed v_{rms}. Given a system of carbon dioxide gas, the speed of the molecules changes based on the temperature of the gas. For carbon dioxide, the speed for some particle in that system can be calculated as the probable speed or v_p, which can be described as:

$$v_p = \sqrt{\frac{2RT}{M}}$$

where R is the gas constant (8.31 kg m^2 s^{-2} K^{-1} mol^{-1}), T is the temperature in Kelvin, and M is the molecular mass of the gas [59].

Using this equation, a sample calculation for carbon dioxide gas at 20 °C would be:

$$v_p = \sqrt{\frac{2(8.31\ \text{kg m2 s-2 K-1 mol-1})(293.15K)}{0.044\ \text{kg mol-1}}}$$

$$v_p = 332.8\text{m/s}$$

Based on these calculations, a carbon dioxide gas molecule at room temperature moves 40 times faster than Usain Bolt's top speed! However, we do not perceive the motion of these molecules because gas molecules move such microscopic distances. The distance traveled by a moving particle between collisions is called the mean free path. For a gas particle at ambient pressure, the mean free path is about 68nm [60].

Now that it is possible to calculate the probable speed of gas particles in a system, this speed can be used to approximate the molecular motion in the visualization. The probable speed is used as a scale factor to indicate relative changes in particle velocity due to temperature. For example, high temperatures correspond to high probable speeds, which are reflected in the velocities of the particle system visualization. To match the parameters for particle systems within Unity, the particle speed must be normalized between 0 and 1 using the max and min speeds. The max and min speeds were calculated between -10 °C and 30 °C (the approximate temperature range for Tidmarsh) to be 315 m/s and 338.4 m/s, respectively. Speeds were normalized using the equation:

$$z_i = \frac{x_i - \min(x)}{\max(x) - min(x)}$$

Once normalized, the speed was assigned as the driving force in the particle system with simulated noise to emulate the diversity in the distribution of speeds. However, this approach only approximates molecular motion by calculating one metric: probable speed. For simplicity, this approach assumes that the distribution of particle speeds remains constant despite variations in temperature while, in reality, the Maxwell-Boltzmann distribution changes with temperature. Future work can take a more comprehensive approach to predict the full range of speeds in a distribution given the ambient temperature.

EXPERIMENTS WITH PARTICLE NOISE TO DETERMINE THE BEST VISUALIZATION TECHNIQUES

In an effort to achieve a visualization that was both sensitive to incoming data and visually interesting, Perlin noise was used to create variations in particle speed given a temperature-sensitive probable speed (Figure 21). Perlin noise is a gradient noise algorithm developed specifically for computer animation applications to increase the realism of textured objects. In this use case, Perlin noise is applied to particles in a system to approximate the particle speeds to the left and the right of the probable speed on the Maxwell-Boltzmann distribution given a calculated probable speed.

To create appropriate variations in particle speed, several parameters that contribute to Perlin noise were tested including frequency, amplitude, damping, and strength. Frequency refers to the number of samples within a period, and amplitude refers to the range of those samples. Damping is a Boolean parameter that, when present, holds the rate of change constant by decreasing the amplitude when frequency increases. Strength controls the intensity within a range of 0-1, where 1 represents the full intensity of the noise. Based on the user needs from the research phase, the visualization should elicit an experience that explores a different time or space scale, feels like a secret discovery, provides an emotional connection, represents a part of a greater whole, reveals surprising information, and hints at a larger pattern but feels incomplete. For each of these needs, small changes in the underlying noise model could produce different effects in color and motion.

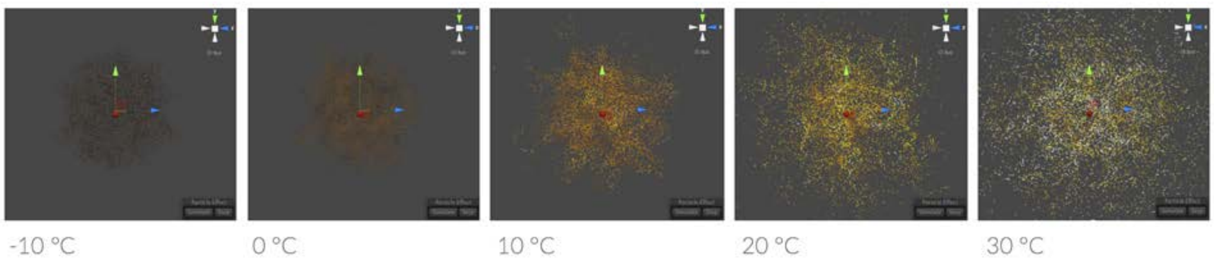

Figure 21. Final model with appropriate parameters that demonstrates changes in color and movement for carbon dioxide gas from -10 °C to 30 °C. These parameters created a balance of order and randomness, with a diversity of visual styles throughout the temperature range.

In these experiments, the color of the individual particles corresponds to a color gradient; the faster the particles move, the brighter the color. In experiments with low frequency and damping off, the particle system feels more “alive” because the movements appear less random (Figures 22 and 23). These settings create a stronger emotional connection and hint at a larger, yet undiscovered pattern. However, when frequencies were too low, the particle system no longer felt like a natural process. These experiments were also used to test how the strength of the noise influenced performance of a particle system given the range of expected velocities (Figures 24 and 25). After these experiments, normalization of the probable velocities was updated to fit within the 0 to 0.5 range as these values produced smooth, cohesive visualizations with strong differentiation between endpoints.

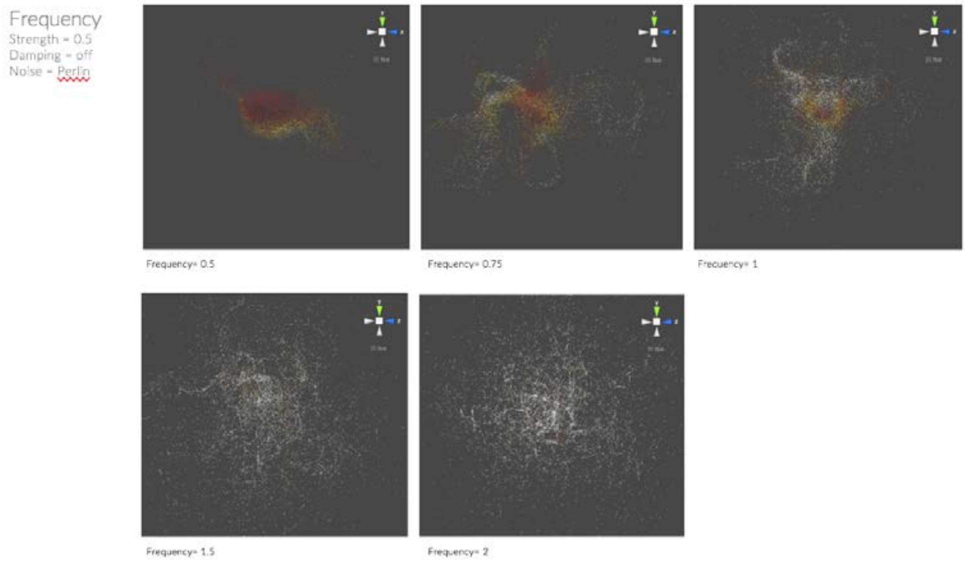

Figure 22. Testing frequency as a parameter for Perlin noise with damping off. Lower frequencies resulted in more "alive" motion, while high frequencies resulted in more random motion.

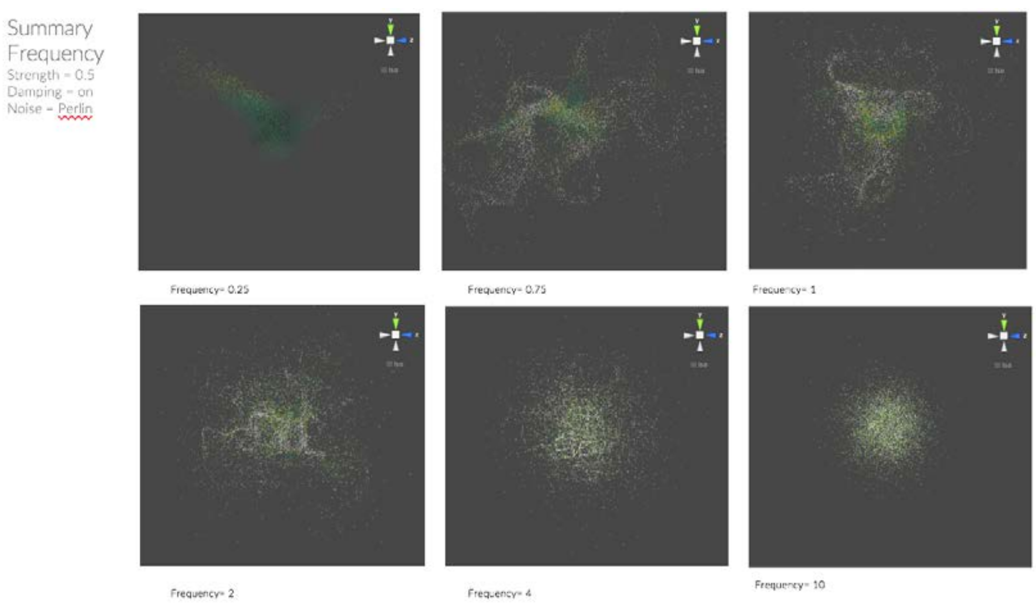

Figure 23. Testing frequency as a parameter for Perlin noise with damping on. Damping the frequency produced a wider range of motion effects.

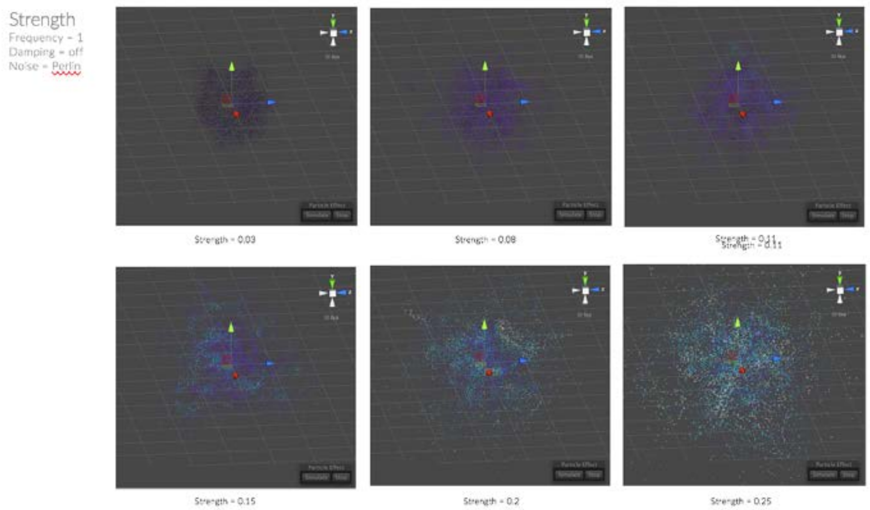

Figure 24. Experiments to test how visual characteristics shift with changes in the strength of the Perlin noise. The lower the strength, the slower and more condensed the system, mimicking the motion of cold gaseous systems. The higher the strength, the faster and more distributed the system, mimicking the motion of hot gaseous systems.

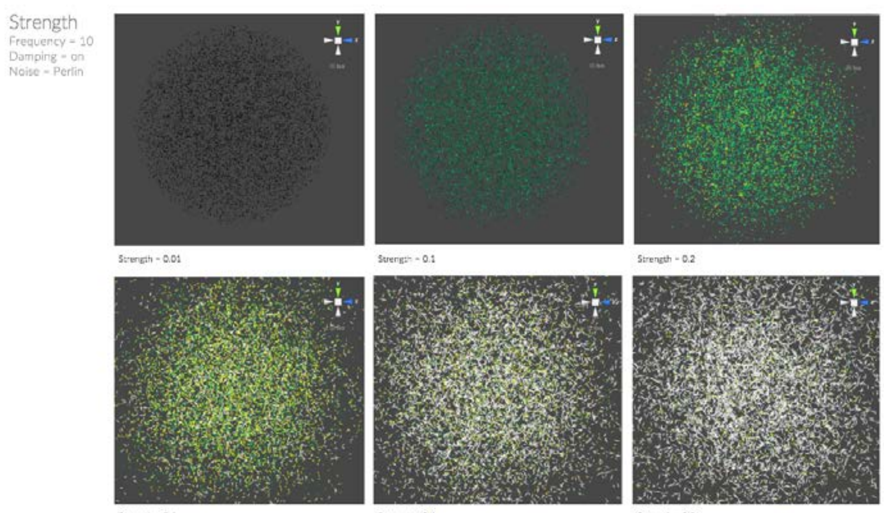

Figure 25. Testing strength at high frequency. While there is very little visual differentiation in the style of particle motion, there is high differentiation in the speed of the particle motion, which is reflected in the color scale.

EcoFlux: Visualizing Ecosystem Processes in Carbon Flow

"When we try to pick out anything by itself, we find it hitched to everything else in the universe."

- John Muir

Mathematical modeling methods for photosynthesis and respiration

Now that the molecular motion driving carbon dioxide particles has been visualized, the next step is to visualize how the carbon flow changes depending on two key processes: photosynthesis and respiration. In an ecosystem, photosynthesis is the process by which plants take in carbon dioxide to produce sugars, and respiration is the process by which both plants and animals produce carbon dioxide as the result of cellular metabolic activity. The rates of photosynthesis and respiration determine whether the environment is currently acting as a carbon sink or a carbon source. These rates are affected by ambient conditions, including temperature, pressure, humidity, illuminance, and soil moisture—most of which are measured by the sensor network at Tidmarsh.

There are many different mathematical models of photosynthesis and respiration, but some of the most complete empirical models have been created by the Institute of Atmospheric Research and Earth System Science (INAR), Department of Forest Ecology of University of Helsinki, Finland [61]. INAR and the National Department of Forest Sciences have collaborated on several projects related to environmental issues and climate change, including research into the carbon balance in forests. Their models provide forecasting tools to describe complex phenomena, but their predictive value is only as good as the variables and assumptions. There are no complete models for photosynthesis in wetlands, so these models provided a proxy for carbon flow despite the assumptions based in temperate forests. INAR was able to validate these models with on-site measurements of gross primary productivity (GPP) as a result of photosynthesis and respiration.

Three major processes contribute to an overall picture of carbon flow in an ecosystem: photosynthesis, or the process of converting carbon dioxide into biomass; plant respiration, or the process by which plants produce carbon dioxide as the result of metabolic activity; and soil respiration, or the process by which soil microbes also produce carbon dioxide as the result of metabolic activity. The sum of these processes determines the net carbon flow in or out of the ecosystem. When carbon flow is negative, carbon is being absorbed by the plants and the wetland is acting as a carbon sink, which is particularly beneficial in the face of climate change. For this thesis, all models for plant photosynthesis [62], plant respiration [63], and soil respiration [64] are presented by INAR as part of the University of Helsinki Department of Forest Sciences CarbonTree project. Note, however, that most wetlands also emit significant amounts of methane due to microbiological activity, which can remove the offset of the carbon sink [65], and this complex and not entirely understood phenomenon is not accounted for in our model.

MODELING SOIL RESPIRATION

Respiration rates change according to environmental conditions, increasing exponentially with temperature. Respiration rates double for every 10°C increase in temperature, but low relative soil water availability limits rates [66]. The effects of soil temperature and moisture can be expressed as the following equation:

$$R = \max[0, f(REW) * r_0 * q_{10}^{T/10} - c_r]$$

where R is the respiration rate, T is temperature, and REW is the relative extractable water (soil moisture). In this model, r_0 =1.1 µmol m^{-2} s^{-1}, q_{10}=2.4, c_r=0.5 µmol m^{-2} s^{-1} and

$$f(REW) = \min[1, \max[0, (REW + d_{rew})/REW_{crit}]]$$

where d_{rew}=0.1 and REW_{crit}=0.6.

Modeling Plant Respiration

As in soil respiration, plant respiration rates exponentially follow temperature and decrease in low soil moisture. This rate can be expressed as:

$$R = \max[0, f(REW) * r_0 * q_{10}^{\frac{T}{10}} - c_r]$$

where R is the respiration rate, T is temperature, and REW is the relative extractable water (soil moisture). Assumptions for this model include, r_0=1.6 µmol m^{-2} s^{-1}, q_{10}=1.5, c_r=0.8 µmol m^{-2} s^{-1}, measured at the temperate forest station in Hyytiälä, Finland. The effect of soil moisture is calculated as:

$$f(REW) = \min[1, \max[0, (REW + d_{rew})/REW_{crit}]]$$

where d_{rew}=0.05 and rew_{crit}=0.35.

MODELING PLANT PHOTOSYNTHESIS

Rates of photosynthesis change depending on the time of the year, the availability of light, the air and soil temperature, and the water availability in the soil. INAR calculates photosynthesis rates using the following mathematical formula:

$$P = f(LAI) * f(PAR) * \min[f(VPD), f(REW)] * f(T) * f(T_{min}) * f(S) * f(CO2)$$

P represents the rate of photosynthesis or the flux of carbon created by photosynthesis, while each contributing factor is defined as its own function f() with parameters. The maximum rate of photosynthesis is driven by leaf area (LAI), light intensity (PAR) and carbon dioxide (CO_2), but other factors limit the rate including air humidity (VPD), days of minimum temperature (T_{min}), temperature (T), the temperature history (S), and soil moisture (REW). Each of these influences can be expressed as their own mathematical models.

LAI represents the "Leaf Area Index":

$$f(LAI) = 1/K * (1e^{K*LAI})$$

where LAI = 8 m^2/m^2 and K = 0.18 at the Hyytiälä measuring site.

PAR represents "Photosynthetically Active Radiation" and is a measure of light intensity:

$$f(PAR) = P_{max} * PAR/(PAR + B)$$

where P_{max}= 9 µmol m^{-2} s^{-1} and B = 600 µmol m^{-2} s^{-1} at the Hyytiälä measuring site.

VPD represents the "Vapor Pressure Deficit" and refers to air humidity, which limits the rate of photosynthesis:

$$f(VPD) = e^{-H*VPD}$$

where H = 0.02 at the Hyytiälä measuring site.

REW represents the "Relative Extractable Water" and refers to the amount of soil moisture available to the plant, potentially limiting the rate of photosynthesis at low amounts:

if $REW \geq REW_{CRIT}, f(REW) = 1$
if $REW < REW_{CRIT}, f(REW) = \max[0, \frac{REW}{REW_{CRIT}}]$

where REW_{CRIT} = 0.45 at the Hyytiälä measuring site.

T represents the current air temperature:

$$f(T) = 1 - e^{c_T*(T-T_0)}$$

where T_0 = –5 °C and c_T = Min [-0.1, 0.5 * (f(S)–1)] at the Hyytiälä measuring site.

S represents the stage of acclimation and refers to the temperature history, which describes the seasonality of photosynthetic activity, i.e. maximum rates in the summer and minimum rates in the winter. Its effect on photosynthesis can be expressed as:

$$f(S) = 1/(1 + e^{c*(S-T_S)})$$

where c = −0.25 and T_S = 5.5°C at the Hyytiälä measuring site.

T_{min} is the minimum temperature in the last 24 hours, which will dramatically reduce the rates of photosynthesis below freezing. It can be expressed as:

$$f(T_{min}) = \max[0, \min[1, (T_{0min} - T_{min})/T_{0min}]]$$

where T_{0min} = −10 °C at the Hyytiälä measuring site.

CO_2 represents the amount of carbon dioxide available to the plant. The more carbon dioxide available, the faster the rate of photosynthesis as defined by this equation:

$$f(CO_2) = (CO_2 - \gamma)/(CO_2 + \gamma + K_{CO2}) * (CO_{2ref} + \gamma + K_{CO2})/(CO_{2ref} - \gamma)$$

where CO_{2ref}=400 ppm, γ=50 ppm and K_{CO2}=500 ppm at the Hyytiälä measuring site.

Additional information on this model of photosynthesis is described by Mäkelä et al. [67] and online at the University of Helsinki Department of Forest Sciences Carbon Tree page [68].

Key Assumptions in the Application of These Models

Although these models are based off numerous assumptions from the Hyytiälä measuring site, the visualization of these models represents the first step in a better quantitative understanding of the ecosystem processes at the Tidmarsh site. It is difficult to measure real-time CO_2 flow into and out of the ecosystem because it requires sensors that are much more precise and expensive than any that would be easily available to the existing sensor nodes. Therefore, the CO_2 flow needs to be estimated from the models and a combination of measured parameters and thoughtful assumptions. We can collect Tidmarsh-specific information, such as leaf area index, to eliminate some of these assumptions and improve the accuracy and relevance of the models. We can also validate the models' predictions through intermittent monitoring of the carbon flux levels to collect ground truth data. Ultimately, both updating the assumptions and verifying the predictions will enable us to develop Tidmarsh-specific models for photosynthesis and respiration.

The prediction of these models is limited by both the quality and type of data collected via the sensor network. For example, the current temperature sensors overestimate temperature in bright sunlight because the sensors are semi-enclosed. Table 6 identifies both the available data and additional assumptions used to visualize these models. Although we have potential access to variables like T_{min}, which reflect the minimum temperature within 24 hours, we need to stabilize our data storage system before being able to update this metric regularly. Several base assumptions were also made for the variables that did have data input from Tidmarsh in the event that the data stream was not consistent.

VARIABLE	DESCRIPTION	RANGE	DATA INPUT	ASSUMPTION
LAI	Leaf Area Index	0 - 20 m^2/m^2	No	8 m^2/m^2
PAR	Photosynthetically Active Radiation	0 - 650 umol m^{-2} s^{-1}	Yes	500 umol m^{-2} s^{-1}
VPD	Vapor Pressure Deficit	0 - 25 g h_2O m^{-3}	Yes	5 g h_2O m^{-3}
REW	Relative Extractable Water	0 - 25 g h_2O m^{-3}	No	0.5 g h_2O m^{-3}
T	Current Air Temperature	-10 - 30 °C	Yes	10 °C
T_{min}	Minimum Temperature	-10 - 30 °C	No	0 °C
S	Temperature History	-10 - 30 °C	No	10 °C
CO_2	Available Carbon Dioxide	0 - 400 ppm	No	400 ppm

Table 6. The variables for the models of photosynthesis and respiration with either the corresponding data inputs via the sensor network or assumptions.

Despite the complexity of the models, there are a few key parameters that strongly influence the rate of photosynthesis, such as available soil moisture or minimum temperature. Therefore, these assumptions were set to demonstrate the rate of photosynthesis under optimal conditions, i.e. without restricting the rate of photosynthesis. As the Tidmarsh project develops additional sensor nodes, it is important to include the metrics that most strongly influence carbon flow, such as soil moisture. Minimum temperature and temperature history can easily be calculated once the database can be queried for historical data.

INTEGRATING SENSOR NETWORK DATA WITH THE MATHEMATICAL MODELS

Additional calculations were necessary to convert the incoming data from the sensor nodes to the correct format for VPD for input into the model. In this calculation, the current air temperature and the relative humidity were used to calculate the saturation vapor pressure (P_{ws}) in hPa as described in the following equation [69]:

$$P_{ws} = A \cdot 10^{\frac{m \cdot T}{T+T_n}}$$

where A = 610.7, m = 7.59, and Tn = 240.73 are constants for the temperature range -20 to 50 °C, and T is the current air temperature in °C.

The P_{ws} can then be converted to the vapor pressure deficit using the following equation:

$$VPD = P_{ws}/100 * RH/100$$

where RH is the relative humidity (in percentage) from the sensor nodes.

These models of photosynthesis and respiration were originally written in javascript for efficient debugging and then translated to C# for implementation in Unity. Once the models were working, the data from the sensor nodes were integrated. The script subscribes to ChainSync and modifies several parameters when the data arrive, providing input for the model. If there are lapses in the data stream, the model defaults to the assumptions. The script is attached to the carbonFlowParticles prefab, which must be instantiated as a child of a SensorNode-0xXXXX as part of the GetResources script in order to receive data.

Once data are received, the script calculates the rates of plant photosynthesis, plant respiration, and soil respiration. If the rate of photosynthesis is larger than the rate of respiration, then a positive gravitational force is applied to the particles in proportion to the rate. As the difference between photosynthesis and respiration rate increases, the particles move faster toward the ground, demonstrating the carbon "sinking" into the biomass. A negative gravitational force is applied if rates of respiration eclipses the rate of photosynthesis, demonstrating the carbon dioxide that the plants and soil are releasing into the atmosphere. Based on the limiting factors affecting the models, Tidmarsh should become a carbon source at night (low luminance), when it is very cold (low temp history), or when it is very dry (low soil moisture), as shown in Figure 26.

Figure 26. Tidmarsh acts as both a carbon sink during the day and a carbon source at night. A high rate of photosynthesis given the temperature and light availability during the day causes the carbon to flow toward the ground as the wetland acts as a carbon sink. At night, the rate of photosynthesis is low and the wetland acts as a carbon source.

Optimizing the Performance for AR and VR to Integrate with DoppelMarsh

For a digital product, it is important to optimize performance so the product can be experienced on a variety of machines. For any AR or VR product, performance is even more important because of the real-time rendering engine. Although isolated particle systems are very performant, the computation increases with the number of sensor nodes and the additional effects in the scene, such as weather and lighting (Figure 27). Therefore, when integrating the EcoFlux particle system into the larger DoppelMarsh platform, there were several problems that resulted in severe lags and dropped frames. After several experimentation tests to understand the cause of the slowdown, the number of particles in each system was reduced (Figures 28 and 29). Instead of spawning and using up computation resources, the particle systems only appear within a certain distance of the player. The sophisticated noise calculations were also reducing the performance, so the type of noise used to create the visualizations was simplified.

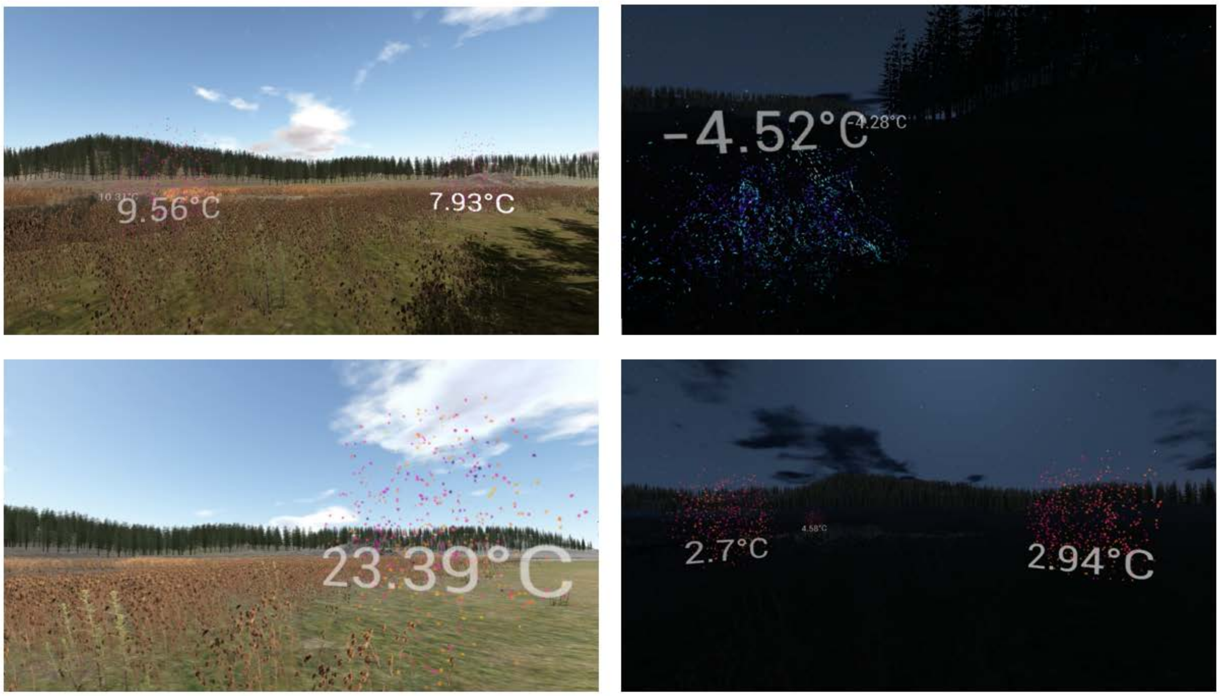

Figure 27. Experiments with color at different times of day to establish appropriate color schemes given the ambient conditions.

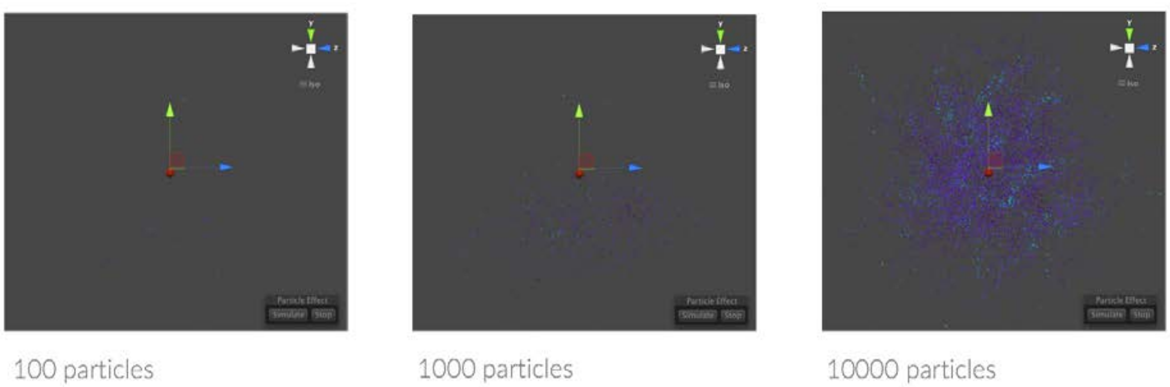

Figure 28. Increasing the number of particles demonstrates the nuances of the visualization, but requires significant computation that decreases performance in AR or VR settings.

Figure 29. An experiment to increase the particle size as a method to increase visibility, but decrease computation expense. Ultimately, the particle size was increased slightly, but the very large particle sizes caused a loss in the larger systematic pattern of movement.

There were significant challenges associated with implementing EcoFlux as an independent application on an AR-enabled device for use in the field. First, the Microsoft Hololens does not work well outdoors due to the bright sunlight and lack of contrast. Second, the Hololens' positioning system SLAM (simultaneous localization and mapping) does not work well in large open spaces devoid of landmarks, such as Tidmarsh's open wetland. Third, there are additional technical challenges when orienting the headset such that the digital world is aligned with the real world. This step is crucial to enable the user to view the visualizations on site at the location of the sensor nodes. Based on these challenges, this proof of concept was only implemented with a VR headset, though it can be implemented with an AR headset once the technology is available.

Connecting the Development Process to the Original Needs List

Throughout the development process, the user needs list informed decisions about the design and development of the final product (Figure 30). Table 7 outlines how the user needs and the themes of inexplicable exploring, social ownership, creature characters, connected presence, information gap theory, curiosity and memory, resolution and relevant, and finding beauty directly influenced the product features for EcoFlux.

USER NEED	**PRODUCT FEATURE**
Experience encourages humans' interest in finding "secret" places.	Visualizations only appear when user is close by, emphasizing the processes are "hidden."
Experience provides opportunities for people to name their experiences so they can share it with others.	Seeing an unseen process enables a user to discuss the process.
Experience creates the same "theory of mind," story-building mindset that people experience when they see animals.	Based on the frequency the noise, the simulation of particles can feel "alive."
Experience emphasizes processes that occur on a scale (time & space) larger than humans usually inhabit.	The visualized processes are taking place at a different time and space scale.
Experience is self-paced to enable people to make their own way in time and space.	The visualization does not require direct input for the user to progress.
Experience creates a new way of seeing the world that people can take with them to other locations and areas.	Seeing carbon flow in action at Tidmarsh can help people imagine carbon flow at other locations.
Experience provides the same emotional connection to the larger ecosystem as humans usually get with animals.	The particles represent a larger process that governs the entire ecosystem.
Experience helps people feel connected and present (both seeing & seen) to the beauty of a natural environment.	The particles respond to the proximity of a user.
Experience connects to something that	Most people are familiar with

humans already know or are familiar with.	photosynthesis and respiration.
Experience reveals information that is “surprising” and causes people to search out more information.	The visualization surprises users with unseen information that may make users more curious.
Experience represents a part of a greater whole—a piece of the puzzle, not the entire picture.	The visualization is just one of many ecosystem processes that are taking place in the wetland at any given moment.
Experience creates an emotional connection that holds our attention.	The particle systems are mesmerizing, especially as they interact with the wetland.
Experience is not a complete answer; it is part of an unexplained mystery.	There are no in-experience explanations for the visualization, so users must explore.
Experience creates one or several key takeaways that people will remember, especially in other environments.	The key takeaway is twofold: there are unseen processes all around us and carbon flow is a good measure of the value of ecological restoration.
Experience hints at a larger pattern and is incomplete; it prompts people to search for what is missing.	The visualization provides a glimpse at the inner workings of an ecosystem, but doesn’t explain them.

Table 7. The human-centered design process yields user needs, which can be mapped to product features so that the final product is desirable, feasible, and viable.

Figure 30. User needs informed the final product design for EcoFlux, tapping into themes of inexplicable exploring, social ownership, creature characters, connected presence, information gap theory, curiosity and memory, resolution and relevant, and finding beauty in this connected landscape.

This page is intentionally left blank

Future Work

Supporting the Future of Tidmarsh

With Mass Audubon's campaign to bring Tidmarsh on as a wildlife sanctuary underway [70], it is more important than ever to document the value of ecological restoration. This thesis aims to provide a foundation for creating engaging and immersive experiences that encourage visitors to be more curious about Tidmarsh and its wild inhabitants. As the number of visitors increases, it is necessary to communicate the wetland's ecosystem services, such as carbon sequestration, denitrification, and storm surge mitigation. These processes operate behind the scenes, and yet they are some of the most beneficial to the entire ecosystem as well as the neighboring community. As part of ongoing DoppelMarsh efforts, new sensors and supplementary projects will continue the Tidmarsh mission of telling the long-term story of the Tidmarsh Farms Wetland Restoration and advancing scientific knowledge and public understanding of wetland ecology.

As new research projects begin, we will continue to learn even more about the key metrics for monitoring and understanding the inner workings of ecosystems. Tidmarsh is a visionary example of a multidisciplinary, science-driven learning collaborative that will continue to engage many different communities for years to come. As our knowledge increases, our insights will drive new techniques and methods for wetland ecological restoration, which can be applied nationally or even globally. Given the current state of climate change and environmental policy, ecological restoration efforts are more important than ever.

FOUNDATION FOR FUTURE WORK

This thesis lays the foundation for visualizing models of ecosystem processes, such as carbon flow. These models contain numerous assumptions that are likely not accurate for Tidmarsh. However, this presents an opportunity to validate and confirm these assumptions as well as test whether the model predictions are correct. For example, collecting metrics like soil moisture, leaf area, and available carbon dioxide at the different sensor nodes will reduce assumptions in the model. Collecting spot measurements on carbon flux will provide a ground truth to verify whether the model is predicting the movement of carbon in and out of the marsh. In addition, the current visualization of carbon only accounts for molecular motion and rates of photosynthesis and respiration. For a true visualization of carbon, the simulation should account for other environmental factors such as wind, which do not affect the rate, but do affect how the carbon dioxide molecules move. EcoFlux would also need include models for methane emissions due to bacterial activity.

Understanding carbon flux is also the first step to visualizing any subterranean communication between plants. This mycorrhizal network has incredible potential as a tool for building empathy and curiosity in visitors to the marsh but presents several challenges, including the lack of information about the factors that affect communication, and therefore no methods to connect any incoming real-time data with meaningful models or visualizations. If we can collect information about the extent of the mycorrhizal network itself, perhaps we could visualize its complexity.

This thesis only explored one modality: visualization of the ecosystem processes. There are more opportunities to develop experiences that take advantage of more of our human senses. The more senses activated, the more complete an experience. In this case, carbon flux could be communication via “data visceralization” or presenting information via synesthesia. For example, increases in carbon flow could be articulated by haptic pulses from a device held by a visitor while exploring the site.

EcoFlux is an experience for carbon flow, but there are several other important processes taking place at Tidmarsh that contribute to its ecosystem services, including denitrification and storm surge protection. As more wildlife return to the site, there are numerous opportunities to communicate food webs, changes in biomass, and biodiversity. Perhaps we can design immersive experiences for sensory landscapes that help visitors develop even more empathy for the wildlife that currently inhabit Tidmarsh’s restored wetland or even the animals and plants that existed thousands of years ago.

Augmented reality provides a completely new means of experiencing the world, but the technology is nascent. With no standard hardware platform, it is challenging to develop applications that provide value and encourage the adoption of these AR-enabled devices. However, given the trends in other areas of emerging technology and the diffusion of innovation, it is likely that AR devices will become increasingly sophisticated in the near future. Eventually, it will be easy to provide an immersive, in-situ experience, such as viewing EcoFlux directly on site at Tidmarsh. This would enable a completely new type of site visit and support Living Observatory's mission at its core. AR will be a truly powerful medium for communicating and supporting collaborative learning.

We are just beginning to scratch the surface of how wetlands respond to restoration, and how restoration can affect the larger ecosystem and human communities. Living Observatory has created an open learning platform with creative partnerships to further exploration and discovery in this magical place. A wealth of information drives millions of environmental processes that we cannot see or hear or feel, but with real-time data collection and new immersive media like AR and VR, we can take one step closer to experiencing the inner workings of ecosystems.

REFERENCES

[1] Dobson, Kelly. (2016). *The Energy Propagated*. http://cargocollective.com/TheEnergyPropagated. Accessed: 2017-05-11.

[2] Mayton, B., Dublon, G., Russell, S., Lynch E., Haddad, D., Ramasubramanian, V., Duhart, C., Davenport, G., & J. A. Paradiso. (2018). The Networked Sensory Landscape: Capturing and Experiencing Ecological Change Across Scales. *Presence*.

[3] Haddad, D. Dublon, G., Mayton, B., Russell, S., Xiao, X., Perlin, K., & J. A. Paradiso. Resynthesizing Reality Driving Vivid Virtual Environments from Sensor Networks. In Proceedings of SIGGRAPH '17 Talks, Los Angeles, CA, USA, July 30 - August 03, 2017.

[4] Who we are. *Living Observatory*. Retrieved from http://www.livingobservatory.org/about/. Accessed: 2017-04-13.

[5] Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecology and management*, *17*(1), 71.

[6] Reid, W., Mooney, H., Cropper, A., Capistrano, D., Carpenter, S., Chopra, K., & Zurek, M. (2005). *Ecosystems and human well-being* Island Press.

[7] Farber, S. (1987). The value of coastal wetlands for protection of property against hurricane wind damage. *Journal of Environmental Economics and Management*, *14*(2), 143-151.

[8] Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological economics*, *29*(2), 293-301.

[9] Hammer, D. A. (Ed.). (1989). *Constructed wetlands for wastewater treatment: municipal, industrial and agricultural*. CRC Press.

[10] Plauny, H. (2000). Shorebirds. *United States Department of Agriculture Wildlife Habitat Management Institute*.

[11] Discover Tidmarsh: Take a Walk on the Wildflower Side. (2017). *Explore Mass Audubon*.

[12] Discover Tidmarsh: Take a Walk on the Wildflower Side. (2017). *Explore Mass Audubon*.

[13] The campaign for Tidmarsh wildlife Sanctuary—The science. Retrieved from http://www.massaudubon.org/tidmarsh-plymouth/the-science. Accessed: 2017-04-28.

[14] Mayton, B., Dublon, G., Russell, S., Lynch E., Haddad, D., Ramasubramanian, V., Duhart, C., Davenport, G., & J. A. Paradiso. (2018). The Networked Sensory Landscape: Capturing and Experiencing Ecological Change Across Scales. *Presence*.

[15] B. Mayton, G. Dublon, S. Russel, D. D. Haddad & J. A. Paradiso. (2017). Tidmarsh living observatory. Retrieved from http://tidmarsh.media.mit.edu/

[16] Mayton, B., Dublon, G., Russell, S., Lynch E., Haddad, D., Ramasubramanian, V., Duhart, C., Davenport, G., & J. A. Paradiso. (2018). The Networked Sensory Landscape: Capturing and Experiencing Ecological Change Across Scales. *Presence.*

[17] B. Mayton, G. Dublon, S. Russel, D. D. Haddad & J. A. Paradiso. (2017). Tidmarsh living observatory. Retrieved from http://tidmarsh.media.mit.edu/. Accessed: 2017-04-28.

[18] Russell, S., & Paradiso, J. A. (2014, December). Hypermedia APIs for sensor data: a pragmatic approach to the web of things. In *Proceedings of the 11th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services* (pp. 30-39). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

[19] Dublon, G., Pardue, L. S., Mayton, B., Swartz, N., Joliat, N., Hurst, P., & Paradiso, J. A. (2011, October). Doppellab: Tools for exploring and harnessing multimodal sensor network data. In *Sensors, 2011 IEEE* (pp. 1612-1615). IEEE.

[20] Lifton, J., & J. A. Paradiso. "Dual reality: Merging the real and virtual." *International Conference on Facets of Virtual Environments*. Springer Berlin Heidelberg, 2009.

[21] Russell, S., Dublon, G., & J. A. Paradiso. (2016). HearThere: Networked sensory prosthetics through auditory augmented reality. Paper presented at the 20:1–20:8. doi:10.1145/2875194.2875247.

[22] Lynch, E., & Paradiso, J. (2016). *SensorChimes: Musical mapping for sensor networks*. Griffith University, Brisbane, Australia.: NIME'16.

[23] Li, Q., Dublon, G., Mayton, B., & J. A. Paradiso (2015). *MarshVis: Visualizing real-time and historical ecological data.*

[24] Lifton, J, and J. A. Paradiso. "Dual reality: Merging the real and virtual." *International Conference on Facets of & Environments*. Springer Berlin Heidelberg, 2009.

[25] Lewis, M., & Jacobson, J. (2002). Game engines in scientific research. *Communications of the ACM, 1* doi://dx.doi.org/10.1145/502269.502288.

[26] Brown-Simmons, G. J., Kuester, F., Knox, C. J. H., & Yamaoka, S. (2009). Earth and planetary system science game engine. In Z. Pan, A. D. Cheok, W. Müller & A. E. Rhalibi (Eds.), *Transactions on edutainment II* (pp. 203-218) Springer Berlin Heidelberg. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-03270-7_14.

[27] Kot, B., Wuensche, B., Grundy, J., & J. Hosking. (2005). Information visualisation utilising 3D computer game engines case study: A source code comprehension tool. Paper presented at the 53–60. doi:10.1145/1073943.1073954.

[28] Cabello, O. (2017). 4 things I learned designing an AR app for NASA. Retrieved from http://blog.invisionapp.com/ux-design-ar-apps/. Accessed: 2017-05-04.

[29] Olshannikova, E., Ometov, A., Koucheryavy, Y., & Olsson, T. (2015). Visualizing big data with augmented and virtual reality: Challenges and research agenda. *Journal of Big Data, 2*(1), 22. doi:10.1186/s40537-015-0031-2.

[30] Ackoff, R. L. (1999). *Ackoff's best* (1. ed. ed.). New York: John Wiley & Sons.

[31] Tufte, E. R. (2013). *Envisioning information* (14th ed.). Cheshire, Conn: Graphics Press.

[32] Tang, A., Owen, C., Biocca, F., & Mou, W. (2003). Comparative effectiveness of augmented reality in object assembly. Paper presented at the 73–80. doi:10.1145/642611.642626.

[33] Lei, H., Xiangyu, W., Leonhard, B., & Love, P. E. D. (2013). Using animated augmented reality to cognitively guide assembly. *Journal of Computing in Civil Engineering, 27*(5), 439-451. doi:10.1061/(ASCE)CP.1943-5487.0000184.

[34] Kelly, B. (2014). Take a guided tour of UK skies. Retrieved from http://nats.aero/blog/2014/11/take-guided-tour-uk-skies/ Accessed: 2017-05-02.

[35] Kelly, B. (2014). Take a guided tour of UK skies. Retrieved from http://nats.aero/blog/2014/11/take-guided-tour-uk-skies/ Accessed: 2017-05-02.

[36] Dobson, Kelly. (2016). *The Energy Propagated*. http://cargocollective.com/TheEnergyPropagated. Accessed: 2017-05-11.

[37] Yi, J. S., Kang, Y. a., & Stasko, J. (2007). Toward a deeper understanding of the role of interaction in information visualization. *IEEE Transactions on Visualization and Computer Graphics, 13*(6), 1224-1231. doi:10.1109/TVCG.2007.70515.

[38] Loewenstein, G. (1994). The psychology of curiosity: A review and reinterpretation. *ResearchGate, 116*(1), 75-98. doi:10.1037/0033-2909.116.1.75.

[39] Loewenstein, G. (1994). *The psychology of curiosity: A review and reinterpretation* doi:10.1037/0033-2909.116.1.75.

[40] Russell Golman, & George Loewenstein. (2014). *Curiosity, information gaps, and the utility of knowledge*.

[41] Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T., & Camerer, C. (2008). *The wick in the candle of learning: Epistemic curiosity activates reward circuitry and enhances memory*. (). Rochester, NY: doi:10.2139/ssrn.1308286.

[42] Ishizu, T., & Zeki, S. (2011). Toward A brain-based theory of beauty. *Plos One, 6*(7), e21852. doi:10.1371/journal.pone.0021852.

[43] Science, Author: Jonah Lehrer Jonah Lehrer.Why does beauty exist? Retrieved from https://www.wired.com/2011/07/why-does-beauty-exist/ Accessed: 2017-04-12.

[44] Oviatt, S. (2006). Human-centered design meets cognitive load theory: Designing interfaces that help people think. Paper presented at the 871–880. doi:10.1145/1180639.1180831.

[45] Ulrich, K. T., & Eppinger, S. D. (2016). *Product design and development* (6. ed. ed.). New York, NY: McGraw-Hill. Retrieved from http://www.econis.eu/PPNSET?PPN=815664621.

[46] Griffin, A., & Hauser, J. R. (1993). The voice of the customer. *Marketing Science, 12*(1), 1-27. doi:10.1287/mksc.12.1.1.

[47] Ulrich, K. T., & Eppinger, S. D. (2016). *Product design and development* (6. ed. ed.). New York, NY: McGraw-Hill. Retrieved from http://www.econis.eu/PPNSET?PPN=815664621.

[48] Lenart, M. (2009). An unseen carbon sink. *Nature Reports Climate Change,* (0912), 137-138. doi:10.1038/climate.2009.125.

[49] Klein, T., Siegwolf, R. T. W., & Körner, C. (2016). Belowground carbon trade among tall trees in a temperate forest. *Science, 352*(6283), 342-344. doi:10.1126/science.aad6188.

[50] Courty, P., Walder, F., Boller, T., Ineichen, K., Wiemken, A., Rousteau, A., & Selosse, M. (2011). Carbon and nitrogen metabolism in mycorrhizal networks and mycoheterotrophic plants of tropical forests: A stable isotope analysis. *Plant Physiology, 156*(2), 952-961. doi:10.1104/pp.111.177618.

[51] Beiler, K. J., Durall, D. M., Simard, S. W., Maxwell, S. A., & Kretzer, A. M. (2010). Architecture of the wood-wide web: Rhizopogon spp. genets link multiple douglas-fir cohorts. *New Phytologist, 185*(2), 543-553. doi:10.1111/j.1469-8137.2009.03069.x.

[52] Jung, S. C., Martinez-Medina, A., Lopez-Raez, J. A., & Pozo, M. J. (2012). Mycorrhiza-induced resistance and priming of plant defenses. *Journal of Chemical Ecology, 38*(6), 651-664. doi:10.1007/s10886-012-0134-6.

[53] Babikova, Z., Gilbert, L., Bruce, T. J. A., Birkett, M., Caulfield, J. C., Woodcock, C., . . . Johnson, D. (2013). Underground signals carried through common mycelial networks warn neighbouring plants of aphid attack. *Ecology Letters, 16*(7), 835-843. doi:10.1111/ele.12115.

[54] Luo, W., Wang, S., Huang, J., Yan, L., & Huang, J. (2007). Impact of photosynthesis and transpiration on nitrogen removal in constructed wetlands. *Frontiers of Environmental Science & Engineering in China, 1*(3), 316-319. doi:10.1007/s11783-007-0053-x.

[55] Evaristo, J., Jasechko, S., & McDonnell, J. J. (2015). Global separation of plant transpiration from groundwater and streamflow. *Nature, 525*(7567), 91-94. doi:10.1038/nature14983.

[56] Charles Xie, The Advanced Educational Modeling Laboratory, The Concord Consortium, & qxie@concord.org. (2010). *Molecular dynamics for everyone: A technical introduc- tion to the molecular workbench software.*

[57] Charles Xie, The Advanced Educational Modeling Laboratory, The Concord Consortium. (2010). *Molecular dynamics for everyone: A technical introduction to the molecular workbench software.*

[58] Claunch, C. (2016). Kinetic theory of gases. In D. Larson (Ed.), *Chemistry LibreTexts* () UC Davis.

[59] Serway, R. A., & Vuille, C. (2012). *College physics* (Volume 1 (9th ed.) ed.). https://books.google.com/books?id=HLxV-IKYO5IC&pg=PA352#v=onepage&q&f=false: Cengage Learning.

[60] Jennings, S. G. (1988). The mean free path in air. *Journal of Aerosol Science*, *19*(2), 159-166.

[61] Mäkelä, A., Pulkkinen, M., Kolari, P., Lagergren, F., Berbigier, P., Lindroth, A., Hari, P. (2008). Developing an empirical model of stand GPP with the LUE approach: Analysis of eddy covariance data at five contrasting conifer sites in europe. *Global Change Biology, 14*(1), 92-108. doi:10.1111/j.1365-2486.2007.01463.x.

[62] Oy, S., Jaskara, M. & Haapoja, T.How to model photosynthesis? Retrieved from http://www.hiilipuu.fi/articles/how-model-photosynthesis. Accessed: 2017-03-15.

[63] Oy, S., Jaskara, M. & Haapoja, T.Modelling shoot respiration. Retrieved from http://www.hiilipuu.fi/articles/modelling-shoot-respiration. Accessed: 2017-03-15.

[64] Oy, S., Jaskara, M. & Haapoja, T.How to model soil respiration? Retrieved from http://www.hiilipuu.fi/articles/how-model-soil-respiration. Accessed: 2017-03-15.

[65] Segers, R. (1998). Methane production and methane consumption: a review of processes underlying wetland methane fluxes. *Biogeochemistry*, *41*(1), 23-51.

[66] Pumpanen, J., Ilvesniemi, H., & Hari, P. (2003). A process-based model for predicting soil carbon dioxide efflux and concentration. *Soil Science Society of America Journal, 67*(2), 402-413. doi:10.2136/sssaj2003.4020.

[67] Mäkelä, A., Pulkkinen, M., Kolari, P., Lagergren, F., Berbigier, P., Lindroth, A., . . . Hari, P. (2008). Developing an empirical model of stand GPP with the LUE approach: Analysis of eddy covariance data at five contrasting conifer sites in europe. *Global Change Biology, 14*(1), 92-108. doi:10.1111/j.1365-2486.2007.01463.x.

[68] Oy, S., Jaskara, M., & Haapoja, T.*How to model photosynthesis?* (http://www.hiilipuu.fi/articles/how-model-photosynthesis ed.) Accessed: 2017-03-15.

[69] Oyj, V. (2013). Humidity conversion formulas. (pp. 1-17) Vaisala.

[70] Discover Tidmarsh: Take a Walk on the Wildflower Side. (2017). *Explore Mass Audubon*.