The Digital Aquarist: An Interactive Ecology Simulator

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Abstract

In this paper, we present an interactive simulation of the ecological cycle in a fish tank. Like the owner of a real fish tank, the user of the simulation has to balance several vital parameters of the aquatic system. Next to people interested in the world of aquatics in general, the simulation especially targets teenagers and aims at increasing their interest in ecosystems, and to contributing to their understanding of basic ecological principles. We engage the user introducing various gamification elements, including game-like UI elements, high scores, and a diligently adjusted reward system that allows for adding new inhabitants to the aquarium. Based on a user study, we evaluate our concept and layout possible improvements and extensions.

Introduction

A profound understanding of complex relationships and processes in ecological systems is an important factor for making informed, sustainable decisions. Like other empirical sciences, ecological research heavily relies on digital tools, including those for storage/retrieval, modelling and analysis (Jones et al. (2006)). Educators have been assembling a similar repertoire of digital tools for teaching ecological systems, whereas computational simulations are especially well suited to convey their inherent, often fragile complexity (Stevenson et al. (2014)).

In this paper, we present *The Digital Aquarist*, an interactive simulation of the ecological cycle in a fish tank. Following the concept of gamification, see e.g. Deterding et al. (2011); Groh (2012), we engage the user in the simulation by providing easy and rewarding access to the model context, to the model mechanics and especially to the offered user interactions. Along the same lines, we reduce the amount of prior knowledge required for a rewarding simulation experience to a bare minimum: (1) The user can easily explore the interdependencies between different organisms by himself. (2) The simulation is staged in a moderately sized fish tank that is often found in private homes (about 6.5% of households keep fish in the U.S. (AVMA, US (2012))).

We further distilled a model complex enough to convey foundational ecological relationships and the emergent system dynamics, yet simple enough to work for an introductory educational setting. The interaction possibilities are part of this model simplification: The user is encouraged to balance the different system variables by adding or removing organisms from the fish tank. Each animal or plant has a certain impact on the ecosystem by either reducing or increasing systemic parameter values, e.g. through breathing. The goal is to keep the schools of fish healthy over a long period of time while increasing the number of inhabitants, and thus the heterogeneity and the complexity of the ecosystems' population.

The remainder of this paper is structured as follows: In the next section, we discuss related work that influenced this project. Afterward, we present our modelling approach, the use of gamification elements, the realisation of aesthetic visualisation and the degree of complexity of the application. Based on our approach, we summarise our accomplishments. Finally, we outline how the simulation could be extended in the future.

Related Work

Creating a closed ecological cycle has been attempted by scientists in various projects. Biosphere 2 is a notable representative project of this kind (Allen and Nelson (1999)). It is an architectural and technological large-scale compound for exploring the interplay between human life and its environment in a closed ecological system. Biosphere 2 had originally been planned as a self-sustaining system. It is used as a research laboratory now, after two attempts to make it work have failed. The same idea but, at least commercially, more successful is the Ecosphere, an aquarium whose inhabitants are completely sealed off from any metabolic exchange with the environment. Only the sun light enters from the outside world and drives growth and transformation processes of the contained plants and animals (Schilthuizen (2009)). Although it is being disputed whether the life stock, the shrimp Halocardina Rubra, is surviving rather than slowly starving to death (Bailey-Brock and Brock (1993)).

Despite their minimalistic approaches and their emphasis on the exploration of well-defined ecological processes, neither Biosphere 2 nor the Ecosphere are apt for learning about and exploring ecosystem dynamics. One reason is the inaccessibility of the given systems. It is barely possible to change any of their compositions. Time scales are another reason: It takes long periods of time for ecological systems to stabilize, rendering it (even more) impractical to proactively change their settings and to explore their dynamics. For these reasons, providing interactive simulations of isolated problem domains, or *microworlds*, has become an important methodological approach in education and education research (Miller et al. (1999); Druin et al. (2014)).

While it has been emphasised that idealised model representations (as opposed to concrete ones) foster the development of generalisable insights (Goldstone and Son (2005)), *The Digital Aquarist* prioritises relatable, engaging aesthetic animation over the abstract display of an expectedly vivid, visually attractive ecosystem. Therefore, different from a preceding, NetLogo-based 2D aquarium model (Tan and Biswas (2007)), *The Digital Aquarist* models the aquarium and its inhabitants in an animated three-dimensional world.

Interactive parameter adjustment of a simulated aquarium has previously been used to study human learning and planning capacity (Vollmeyer et al. (1996)). It could show that promoting the free exploration of a dynamic system allows the user to gain general knowledge, whereas addressing specific tasks would solely foster specific knowledge. We harness this insight by allowing the users to freely explore our simulation and to only provide implicit stimuli to maintain the aquarium over time and with growing heterogeneity. However, as the investigation of intellectual capacities is not the *The Digital Aquarist*'s goal, we also reveal detailed information about the inhabitants of the simulation and their relationships, if inquired by the user.

Methodology

For the sake of accessibility, we focus on simple visuals and avoid overburdening the user with information which would, very likely, jeopardise the attractiveness of the simulation (Steele and Iliinsky (2010)). Instead of promoting formal analytical skills, we make sure to provide visible feedback similar to real-world experiences, including rampant algae growth upon eutrophication or starving fish. To keep the user both interested and involved, we built the simulation on the three "pillars of fun" (Koster (2013))—relatedness, competence, and autonomy: (1) Relatedness is established by the fact that aquaria may exist in households similar to the ones the potential users of the simulation call their home (see Figure 1). The great number of aquaria worldwide renders it likely that the users are even familiar with the concept of keeping ornamental fish, possibly also the notion that the aquarist needs to ensure an ecological balance. Finally, we establish a connection between the user and the simulation by showing that initially the virtual aquarium is empty and thus that he is responsible for each and every one of its inhabitants. (2) To promote the competence of the user, he needs to be challenged without giving rise to frustration. This goal is supported by the facts that *The Digital Aquarist* builds an ecosystem one step at a time, that the user always has the power to change its configuration back to a previous, simpler state, and that he can pro-actively inquire information about the aquarium's inhabitants and their relationships. To ease the user into the simulation scenario, he may enter a tutorial level from the main screen (Figure 2) and step through a guided tour shedding light on the impact of different species on the ecosystem. (3) *The Digital Aquarist* provides an inherently autonomous user experience in that it does not enforce the fulfilment of specific tasks but it lets the user explore the aquarium dynamics on his own. A high score system is provided that rewards the user's achievements but it does not limit the potential of exploration.

Figure 1: The simulated aquarium placed on a cupboard signals an everyday real-life scenario. The user interface aligned at the border of the view invites the user to join a playful simulation session.

Figure 2: From the main menu of *The Digital Aquarist*, the user may access the high score list, enter a tutorial or join an endless explorative simulation session.

The Aquarium Model

In order to ensure an ecological equilibrium, several variables that describe a fish tank's state have to be maintained at certain levels. The main parameters are the levels of oxygen, carbon dioxide, nutrient matter in the seabed, the water volume, and the unoccupied space in the tank. Other important factors are the hardness of the water, its temperature, and the tank's light exposure. To allow the user to focus on key aspects of the ecological cycle, the latter two aspects are neglected in our model. In a real aquarium, these factors have to be adjusted by means of external devices.

The user can balance the aquarium parameters by adding and removing various animals and plants which all have their own way of interacting with the system. The amount of plants impacts the amount of nutrient matter in the water and the seabed, the levels of oxygen and carbon dioxide in the water, as well as the amount of unoccupied space in the tank. Seaweed breathes in carbon dioxide and breathes out oxygen, takes nutrient matter out of the seabed and releases small particles of nutrient matter into the water.

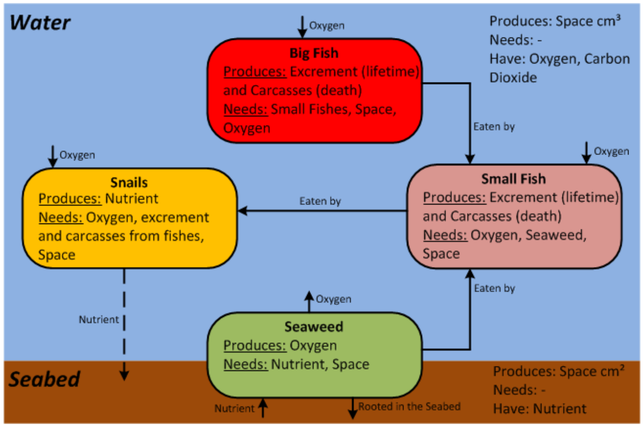


Figure 3: Overview of our fish tank ecosystem model.

Figure 3 provides an overview of the inhabitants of the aquarium and their impact on the ecosystem. Nutrient matter in the water is consumed by the fish. The snails add the fish' excrements to the seabed. The seabed in turn serves as a nutritional basis for the seaweed. Small parts of the seaweed that break away and enrich the water are picked up by the fish again. The seaweed also produces the oxygen snails and fish breathe and absorbs the carbon dioxide they produce. This cycle can be disrupted by fish either eating smaller peers or seaweed in great quantities, which happens if there is not enough nutrient matter in the water.

Organismal Interdependencies The food intake of the fish scales with their size/age. Next to fish and plants, snails populate the virtual aquarium. Both micro-organisms and snails transform the fish' excrements in the water in nutrient matter that agglomerates in the seabed. This mechanism completes the nutrition cycle in the system. In order to provide ample visibility, the presence of snails also represents the transformative power of micro-organisms in our simulation. This means that snails are the only organisms accessible to the user that filter dirty water (from fish excrements) and feed nutrients into the seabed. In reality these processes would be addressed by both snails and micro-organisms. Same as fish, snails breathe in oxygen and breathe out carbon dioxide.

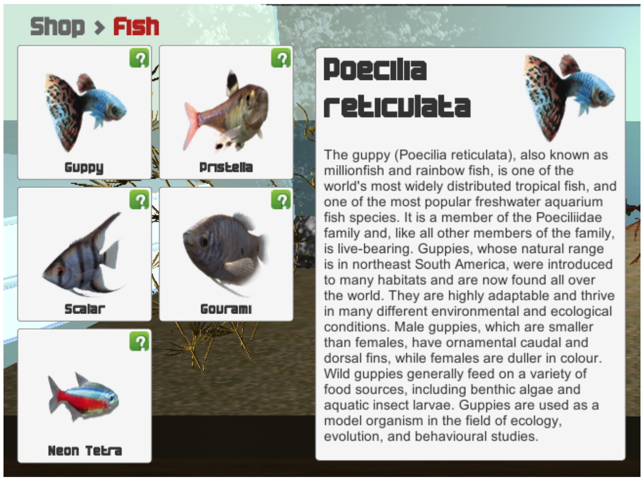
For the user to create a closed ecosystem, he needs to add members of each class of organisms and ensure that their mutual impacts keep a nice balance. Fish and snails need to breathe in a certain amount of oxygen and need the carbon dioxide to be below a certain level to keep from suffocating. Plants need to breathe in a certain amount of carbon dioxide, otherwise they suffocate. Fish need to absorb nutrient matter from the water, snails filter the fish' excrements, and seaweed absorbs nutrient matter from the seabed.

Additionally to the aforementioned interdependencies, each organism takes up a certain amount of space. When the fish tank gets too crowded, the fish will get stressed and will be unable to procreate. The procreation of fish adds another layer of complexity to the system. Due to the procreation of the fish, the user cannot easily anticipate the needed amount of inhabitants of the aquarium before starting the simulation. Therefore, the user needs to react to changing conditions on the fly, either by removing individual fish or by providing more nutrient matter, as well as snails and plants to find a new equilibrium.

Model information about the individual organisms is made available to the user on demand. A shopping interface allows to choose and add organisms to the ecosystem. The user needs to earn virtual currency to buy the organisms in the store. He earns coins by keeping animals and plants alive for as long as possible. This positive feedback mechanism ensures that the user is not immediately overwhelmed by a great number of organisms in the tank and also that fewer expensive organisms are added at first that are harder to cope with. At the same time, keeping a healthy ecosystem is directly translated into a rewarding sensation with actual impact on the interaction possibilities.

Currently, a selection of five fish is offered in the virtual store. Their impact on the ecosystem only differs due to their different sizes which in turn affects their metabolic rates. Otherwise, they all play the same role in the system. That means that all fish breathe in oxygen, consume nutrient matter, emit carbon dioxide, and leave excrements behind. Yet, the respective amounts vary from species to species. The store interface also provides additional information about the organisms, as exemplarily shown in Figure 4.

Modelling Metabolisms There are several model assumptions that have been made to keep the model complexity manageable. In particular, we assume a constant water tem-



Poecilia reticulata

The guppy (Poecilia reticulata), also known as millionfish and rainbow fish, is one of the world's most widely distributed tropical fish, and one of the most popular freshwater aquarium fish species. It is a member of the Poeciliidae family and, like all other members of the family, is live-bearing. Guppies, whose natural range is in northeast South America, were introduced to many habitats and are now found all over the world. They are highly adaptable and thrive in many different environmental and ecological conditions. Male guppies, which are smaller than females, have ornamental caudal and dorsal fins, while females are duller in colour. Wild guppies generally feed on a variety of food sources, including benthic algae and aquatic insect larvae. Guppies are used as a model organism in the field of ecology, evolution, and behavioural studies.

Figure 4: Additional information about a guppy fish is offered to the user in the virtual shopping interface.

perature of $20°C$, we do not consider the day/night cycle, we consider $9mg/l$ of oxygen as fully saturated freshwater (Dean L. Shumway (1964)), $50mg$ O_2 consumption per $100g$ of fish body weight per hour (Brett (1972)), $5mg$ O_2 production by $1g$ of algae per hour, and a $10sec$ integration step size of the simulation.

Table 1 lists the model variables involved in the calculation of the degree of oxygen saturation in the tank. The binary function $oCO_2(t)$ indicates whether or not a surfeit of carbon dioxide can be determined at time step t, i.e. a CO_2 value greater than or equal to twice the standard level of CO_2 is detected.

$h, w, d \in \mathbb{R}^*_+$	fish tank dimensions (cm)
$c \in \mathbb{R}^*_+ = h \times w \times d$	fish tank capacity (cm^3)
$li \in \mathbb{R}^*_+ = c/1000$	fish tank capacity (litres)
P	set of all plants
A	set of all animals
$O_2(t) \in \mathbb{R}^*_+ = li * 9$	amount of O_2 (in mg) at time $t = 0$
$i = 10$	integration step size (seconds)
$oCO_2(t) \in \{0, 1\}$	strong over saturation of CO_2 at time t

Table 1: Model variables for calculating oxygen saturation.

Based on the given variables, we calculate the amount of O_2 (in mg) at time t according to Equation 1. The oxygen saturation level is the ratio of current oxygen in the system relative to the initial oxygen level at $t = 0$. In conclusion, the oxygen saturation is influenced by the amount of oxygen produced and used by each organism in the fish tank. Exemplary values for the O_2 consumption of model organisms are listed in Table 2, whereas the intake is negative for algae since they produce oxygen.

$$\begin{aligned} O_2(t) = O_2(t-1) + \sum_{p \in P} O_2(p) - \sum_{a \in A} O_2(a) \\ - (\sum_{a \in A} O_2(a) * 0.25) * oCO_2(t-1) \end{aligned} \tag{1}$$

species	body weight	O_2 intake
Pterophyllum scalare	$300g$	$0.42\ mg/i$
Poecilia reticulata	$10g$	$0.014\ mg/i$
Aponogeton ulvaceus	$50g$	$-1.39\ mg/i$
Alternanthera reineckii	$100g$	$-2.78\ mg/i$

Table 2: Exemplary values of O_2 intake of model organisms.

Figure 5 shows an exemplary evolution of the oxygen saturation level. Until $t = 4$, 24 fish (12 *Pterophyllum scalare* and 12 *Poecilia reticulata*) slowly decrease the level of oxygen in the aquarium, despite the presence of two plants (*Aponogeton ulvaceus* and *Alternanthera reineckii*). At $t = 4$, one of the two plants dies off and the oxygen depletes twice as fast as before. The lack of oxygen leads to suffocation of 21 fish at $t = 7$ which results in the recovery of the oxygen saturation rate based on one remaining plant.

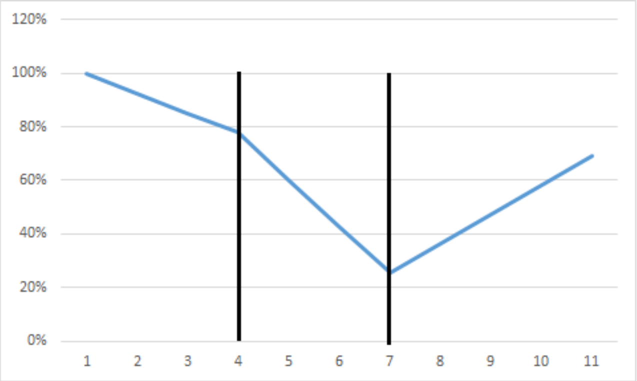


Figure 5: Oxygen saturation over time.

The amount of nutrients, the amount of dirt and the amount of carbon dioxide are computed in the same way as oxygen. Yet, the according equations consider the different organisms' impact on these variables. In case of nutrients in the water, the organisms take on the same role as for the oxygen level—plants increase their level, animals reduce it. Only the actual values of nutrient matter provided and consumed differ. The roles of the organisms are switched in terms of carbon dioxide, i.e. animals exhale CO_2 output and plants consume it. Dirt arises from the set of all fish

F and is diminished by the set of all snails S, resulting in Equation 2.

$$Dirt(t) = Dirt(t-1) + \sum_{f \in F} Dirt(f) - \sum_{s \in S} Dirt(s) \tag{2}$$

Simplifications Balancing complexity and accessibility, we have setup an approximative model. Therefore, we have to investigate the impact on the model accuracy conveyed to the user. The fish offered to the user to populate the aquarium resemble two popular ornamental species, the guppy and the scalare. The guppy mainly feeds on zooplankton which is living plankton, in the simulation it feeds on plankton produced by seaweed (fishbase.org (2015a)). Scalare are known to eat small fish as portrayed in the simulation (fishbase.org (2015b)). Snails do have a cleaning effect on the fish tank, yet they usually eat leftover food and algae (planetinverts.com (2015)). As mentioned before, the snails also visually represent the role of micro-organisms in the ecosystem, to empower the user to easily trace and influence the delicate dependency network.

Despite its simplifications, the current model conveys foundational interdependencies an aquarist needs to be aware of. Therefore, we feel the overarching goal of educating about ecological systems' dynamics is not weakened. Yet, we would like to identify and integrate new ways of high-level visualisations for improving the model accuracy without jeopardising *The Digital Aquarist*'s accessibility.

User Challenges

The learnings of *The Digital Aquarist* result from freely exploring, learning (primarily) by trial-and-error, and mastering a potentially great complexity of an ecosystem. They include a notion of the basic interdependencies of the interacting species as well as their evolution over time: Depending on the metabolic status of the aquarium and the configuration of its population, the effect of adding individual organisms to or removing them from the tank is delayed. In order to successfully manage the aquarium, the user has to anticipate these developments. This is especially challenging as each organism influences more than one system variable.

Without user intervention, the collapse of the ecosystem might accelerate, for example by hungry guppies eating seaweed as seen in Figure 6. Devouring seaweed further lowers the amount of plankton in the water, thereby making food an even scarcer resource. This example illustrates how easy it is to disturb an ecologically balanced system and that restoring that balance is not easy, especially if many different species are involved.

User Interface

Figure 6: Guppies eating seaweed due to a lack of plankton in the water.

As seen in Figure 1, three system variables (O_2, CO_2, and dirt) are represented by gauges which enable the user to check the current levels at a glance. Coloured segments indicate the criticality of the respective variables, whereas green indicates a favourable situation, yellow requires the user's attention and red underlines a fatal system state. An increasing level of dirt is also reflected by the water gradually turning green (Figure 7). The icons on the left-hand side of the screen indicate the duration of the simulation in progress, the cumulative score and the overall satisfaction of all organisms in the tank. These information are represented by the timer, the diamond and the smiley icon, respectively. The levels of nutrient matter in the seabed and water are displayed as numbers on the right-hand side of the screen, as the only restriction for them is not to reach zero. Since the fish tank provides limited space it is important for the user to know how many more fish and plants he can add to the system. Therefore on the lefthand side there are indicators how much space in cm^2 is left for plants in the seabed and how much space in cm^3 is left in the water for fish. The user interface enables an intuitive understanding of the status quo and quickly provides feedback about the ecosystem's evolution.

It is important to invest effort into the visual appeal of an interactive aquarium simulation—after all, ornamental fish are not only kept for the fascination for living organisms only but also for their elegance and beauty. Figure 8 shows the flocking of fish which mimics a life-like behaviour and a realistic look of aquarium. The flocking behaviour of fish was implemented according to the boid concept by Reynolds (1987). Here, each individual moves in accordance with its neighbours (Figure 9). In particular, it is urged to keep a minimum distance from its peers (*separation urge*), to flock towards the average location of its neighbours (*cohesion urge*) and to align its velocity with their average velocity (*alignment urge*). We generate circular waypoints throughout the aquarium to let the schools' movement appear naturally.

Soothing background music creates an inviting, relaxing

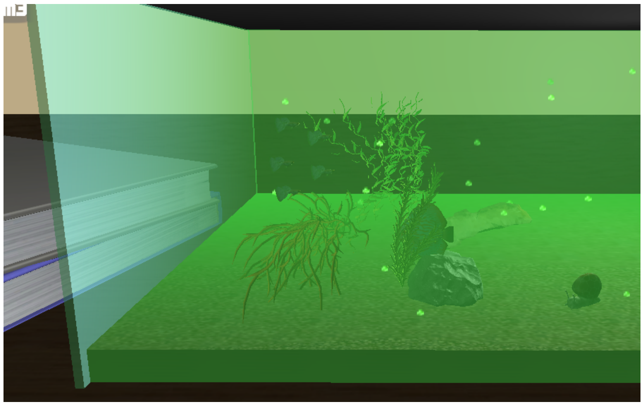


Figure 7: The water gradually turns green with an increasing degree of dirt.

atmosphere. Typical sounds of aquarium pumps and occasional oxygen bubbles popping on the surface help the user feel immersed into the simulation.

Figure 8: A school of guppies animated in accordance with the boids model (Reynolds (1987)).

Discussion

The user can effectively balance the system variables by adding and removing organisms to and from the aquarium. He is rewarded for using more complex scenarios by a scoring/virtual currency system. In particular, higher scores are achieved when hosting bigger fish like scalares rather than relatively small guppies. The earned points can be spent on further additions to the aquatic ecology. We made *The Digital Aquarist* available online and invited colleagues and acquaintances by means of email lists and social media postings to evaluate it. In the according online survey, 31 testers provided anonymous feedback.

Table 3 shows their ratings regarding general aspects of *The Digital Aquarist*. From left to right, the percentages of testers reflect which aspects were "very poor, poor, fair, good, or excellent" (represented as "$--, -, o, +, ++$" in the table). A majority felt that the topic of the game was a good choice, that the model complexity was appropriate, that *The Digital Aquarist* was easy to use and provided some fun. The aesthetics of the game and the learning effect were mainly rated as "fair", the intuitiveness of the game mechanics was rated as "poor". The latter fact stroke us as particularly interesting as the game mechanics are aligned with the model facts the users would learn—if they were considered intuitive in the first place, there would be little knowledge that could be learned. And indeed, a majority of testers felt that they had learned about ecological balance $(44,44\%)$ and about aquarium ecologies in particular $(48,15\%)$. These opinions were supported by some multiple choice questions that inquired about the aquatic organisms' interactions. A great majority of testers recognised facts about the metabolism of fish, snails, and seaweed. Yet, their feeding habits were not as clearly understood. For instance, 11% of the testers erroneously thought snails contributed to the pollution of the water, only about 40% realised that fish eat other fish (which only happens if other food sources become scarce), and only 26% recognised that seaweed was involved in nutrient production.

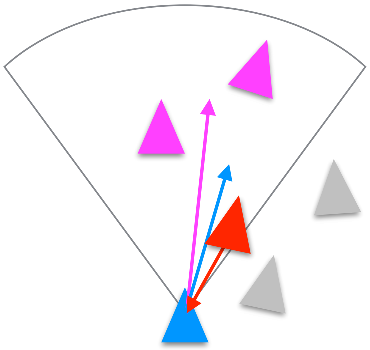


Figure 9: The boid flocking model considers cohesion towards perceived neighbours (pink arrow), separation from peers that are too close (red arrow) and alignment with the neighbours' average velocity (blue).

Summary & Future Work

The Digital Aquarist provides a small-scale ecosystem based on simplified metabolic models. An accessible user interface is supported by animation, visualisation and audio tracks to provide for an open-ended simulation experience that conveys the delicate balance needed to maintain a complex system.

A user survey of our first implementation of *The Digital Aquarist* indicates that we have successfully addressed certain challenges, including finding a proper level of abstraction of the simulated model as well as providing the

	$--$	$-$	o	$+$	$++$
Game Topic	0	12,9	25,81	**45,16**	16,13
Aesthetics	3,23	6,45	**38,71**	35,48	16,13
Model Complexity	0	12,9	32,26	**48,39**	6,45
Fun	16,13	16,13	25,81	**29,03**	12,9
Learning Effect	12,9	12,9	**41,94**	25,81	6,45
Intuitiveness of Game Mechanics	3,23	**35,48**	19,35	25,81	16,13
Ease of Use	6,67	10	20	**40**	23,33

Table 3: Ratings (in %) of different aspects of *The Digital Aquarist* provided by 31 anonymous testers.

necessary accessibility. Yet, we also appreciate that there is leeway for further improvement. Component-based development environments render it quite easy to setup intricate tracking shots that could allow the user to follow individual fish or snails, to experience the ecological processes in a more immersive manner and to reveal interactions close-up. These perspectives could be supported by intricate animations, for instance based on particle systems, to clearly visualise organismal activities such as nibbling, eating, and excreting. In addition, diagrammatic augmentation could drastically speed up the learning process, indicating the relationships among the organisms on demand. In order to keep the user interested over a long period of time, the repertoire of available species, decorative items, and technical add-ons could grow after successfully mastering a balance for a given timespan. Along these lines, one should even consider providing different sizes, shapes and kinds of aquariums. The iconic fishbowl bears different possibilities and challenges than a saltwater tank.

We have scheduled a demo/play event for teenagers, our targeted user group. Based on its success, we are planning the public, mobile release of *The Digital Aquarist*.

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