Qualitative Simulation of an Artificial Life Ecosystem

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Abstract

In this paper, we describe an approach to artificial life, which uses Qualitative Reasoning for the simulation of life within a 3D virtual environment. This system uses qualitative systems to describe both the physiology of a virtual creature and its environment. We illustrate this framework by revisiting early work in Artificial Life and providing these virtual life forms with a corresponding physiology, so as to obtain complete living organism in virtual worlds

1 Introduction

Previous work on Artificial Life has mostly considered molecular physiology, rather than higher level systems, with a few exceptions [Grand et al., 1997]. However, one of the real challenges for the simulation of artificial life consists in being able to represent complex physiological functions to simulate more complex organisms. Our approach has been to use symbolic reasoning instead of differential equations and numerical methods. By this method, we are defining artificial physiology from first principles which opens new ways for the experimentation of artificial alternative life forms.

Using a symbolic description, a qualitative modeller could devise a complex system that represents physiological phenomena from a library of common physical processes. The advantage of modelling such a system using Qualitative Reasoning is that, using a suitably compositional approach for a model, it allows the modeller to produce simple model fragments that combine to give the required complexity for the organism behaviour and produce results in real-time. The challenge in this method for model creation is choosing the best level of description and how to combine the model fragments that are produced from the analysis to create the world and phenomena for the artificial creature.

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The system has been used to develop a virtual creature with internal processes and organs that react to changes in the environment. This work has evolved from research in A-Life that aimed at creating imaginary life forms [Bec, 1991, 1998]. In addition to the creature, the environment has been simulated and integrated with the creature, which allows effects such as hot and cold currents, concentrations, and vortices to affect this creature through the qualitative simulations.

In the remainder of this paper, we present the results from our ongoing research into the use of qualitative processes to simulate both creatures and "ecosystems" for artificial life within a 3D environment. We start by describing the architecture that has been implemented using a game engine, Unreal® Tournament 2003 (UT 2003), and takes advantage of its event-based system to integrate qualitative process theory in an interactive fashion. Following this are case studies into the visualisation of the processes within the virtual creature and its environment. In particular, we show how, due to the basic physical processes, we are able to instantiate multiple model fragments in the creatures' environment and have them interact with it. For example, we present an implementation of the artificial life form within a virtual "Ecosystem" as a test environment. This environment has been implemented as a fully immersive virtual reality system that the user can explore. In this virtual world, we have implemented various behaviours: for physical environment behaviour and for complex organ behaviour which are simulated in user real-time. We conclude by discussion of the work completed so far and present our plans for future research in to expanding the environmental effects into a self contained ecosystem.

2 System Architecture

Our implemented system is composed of two modules whose functions encapsulate that of a visualisation engine, which displays the real-time motion of the virtual creature, and a qualitative simulation engine controlling the simulation of both the internal physiological processes of the creature, and of physical processes in its liquid environment (such as currents, heat flows, diffusion of nutrients, etc.). The integration of qualitative simulation relies on the native event system that has been extended to allow specific events that activates the QP simulations from the interaction with virtual world objects. The UT2003 tm engine has a set of basic events, generated by the graphics engine from collision detection. The UT2003 tm engine supports the extension of these basic events via an embedded scripting language, Unreal Script. The Unreal script language controls every aspect of the environment from the 2D interface the user sees to the creation of 3D objects and management of their animation states. Through the use of this scripting language, we have derived a new set of events for the system, which we call Qualitative Physics events (*QPEvents*). As Shown in Figure 1. For example, when the creature enters or exits a volume the basic event exit_QPVolume and enter_QPVolume are sent to the simulation. These events stop the active processes between the exited volume and activates the processes within the new volume.

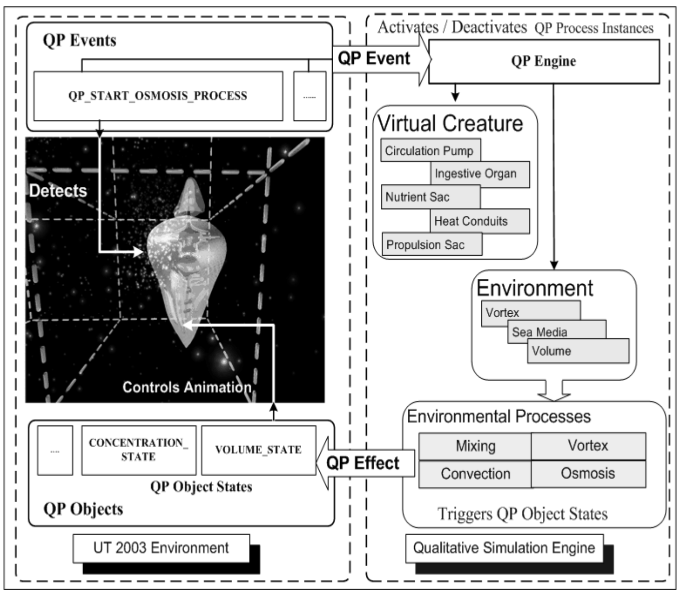

Figure 1: System Architecture

Our system is designed to operate both on standard desktop and within immersive systems. The immersive system we use is a CAVE™-like system called a SAS-Cube™ the configuration of which consists of a four-sided PC-based hardware architecture that is powered by an ORAD PC cluster. The creature is shown within this immersive virtual reality system in Figure 2.

The QR Engine utilises the technique for qualitative simulation of physiological systems [Cavazza and Simo, 2003], derived from Qualitative Process Theory (QPT) [Forbus, 1984] which we refer to as Qualitative Physiology. Qualitative Physiology represents the physiological processes governed by physiological laws using the process-based formalism of QPT, and supports the real-time simulation of physiological sub-systems.

As the QP events involve objects, which are part of the simulation, they trigger the updating of relevant qualitative variables in the QP engine, hence prompting a new cycle of simulation.

In a similar fashion, to present the effects of the simulation to the visualisation engine we have devised *QP_Effects*. These effects utilise the discretisation of the qualitative variables namely the "landmarks" and "limit points". When a qualitative variable passes either a landmark or limit point, a *QP_Effect* is generated and sent to the graphical environment, to trigger changes in visual appearance corresponding to the landmarks reached. Also when the processes become active or inactive *QP_Effects* are generated. This facilitates the opportunity to produce a variety of visualisations, such as particle systems for fluid motion or colour changes for concentration. This is achieved within the Qualitative system after the resolution of influences, by testing the relevant quantities when applying the processes influences. During this testing, the qualitative system can generate an event each time the quantity changes, by generating an event immediately, or can generate an event only when the landmark is passed by testing the quantity space.

Figure 2:Interaction with the Virtual Creature in an Immersive Display

The software architecture for the communication of these *QP_Events* and *QP_Effects* utilises the UDP protocol for transmission between the qualitative simulation engine and the visualisation engine, [Cavazza at al, 2003].

The creation of the artificial creature includes the description of its anatomy and its physiology. The anatomical structure of the artificial creature is briefly outlined in Figure 4: Overview of Physiology. The visual contents have been produced using 3D modeling and animation packages such as 3D Studio Max™ and XSI™. The native 3D models as well as animations have been imported into the UT 2003 engine. These graphical representations can describe, through the use of key-framed animation, the behaviours and actions for the virtual creature. In our scenario these animations represent movements of internal organs, changes in shape of the creature, as well as locomotion and since the simulation is controlled through the use of QP Events we retain the interactive nature of the simulation.

We have described several physiological processes for the artificial virtual creature, dealing with elementary physiological functions such as nutrition, locomotion, and certain homeostatic processes such as thermal regulation. An essential aspect is that these are defined altogether as an integrated system, which can further be refined through experimentation, as the process description is highly modular and processes only connect through characteristic physiological variables (e.g., concentration in nutrients, temperature in certain organs, etc.). Defining the creature using this level of description is largely a functionalist approach [Bedau, 1992], although a top-down, non-emergent one.

3 Implementation

The QR Engine performs all the simulation tasks for the system from the simulation of the environment to the management of any internal physiological phenomena each of which are defined as smaller scenarios. The creation of these smaller scenarios is achieved through the use of a representational language that defines and establishes the simulations for the world. Our qualitative process representations are encoded in our modelling language that is strongly associated with the qualitative process theory. The input the modeller has to the system is to define a domain theory and a scenario. The domain theory consists of a set of defined entities and a set of definitions for phenomena for the domain. The modeller can use the types defined within the domain and applies them to the objects within the 3D environment. These assignments are recorded in the scenario file. For instance, objects can have materials attached to them which give them the default properties for the material which allow them to participate in the processes associated with those properties. This method allows the implementation to be compositional. For instance if we define an entity as a container it can contain substances and its properties only reflect those that we are interested that relate to the amount of substance it can hold. If we wish the container to also participate in thermal processes we must attach thermal material properties to it**.** In the scenario we define vital fluid to be a basic material which is affected by the qualitative processes such as heat flow, fluid flow, osmosis, etc. This domain model serves as a starting point for qualitative simulation. These *QP_Events* and *QP Effects* are used by the system to determine which events and effects the entities can respond to. For instance, the creature absorbs nutrients from the environment so the entry/exit from one volume to another will affect this process. An example of the scripting for the explicit relations between quantities in an entity is provided in the Figure 3. This relation script is applied by the QP Engine after the resolution of influences has determined which of the direct (process) influences are active and has resolved any of the influence conflicts which may exist. Thus the changes within the heat parameter can be applied to the indirectly influenced parameter. However, a relation may only be applicable under certain conditions so the script for the parameter must check if the object has the correct view instance which is represented by a *QPState* variable for the entity. The script implements the explicitly defined function allowing changes in the heat quantity to indirectly influence the entities temperature parameter.

Individuals: Heat Conduits
Preconditions:
Organ QPState = Active
Quantity Conditions:
NONE
Relations:
ΔTemp = ΔHeat /Conductivity*Mass

Figure 3: Example for Heat Relations

In order to create the knowledge representation required to implement a given scenario, the modeller defines the domain for the scenario and then applies the definitions for the entities and model fragments within the environment.

3.1 Implementation for Qualitative Physiology

The formalism adopted within our system allows the creation of a physiology for the creature by the instantiation of Qualitative Reasoning formalism. To achieve this we began with a 3D representation of a creature and a description of the function which each organ performs. This allowed us to isolate a number of distinct yet connected physiological systems that we describe via qualitative processes.

Since we were creating an advanced creature, which consists of multiple organs, the first logical stage was to begin the simulation by creating a model which could provide a basis for the integration of physiological sub-systems. This model concerns the flow of a vital fluid around the creature. Therefore, the first organ defined was a circulatory pump, which was modelled after its mechanical equivalent. The interconnection of the organs would then allow the model to transfer the body fluid. This basic operation allows use to check the viability of homeostasis and a basic bodily cycle working in this state was formed for the creatures resting state.

Initially, we had defined the organs to be containers for a basic entity, which represents the bodily fluid. To advance the model we began by developing processes that occur within the organs to do this we expanded our basic entity for the bodily fluid. The basic entity for the creature is the bodily fluid entity that represents a vital fluid for the creature. We expanded our representation of a fluid to provide a means for the transportation of the elements that are critical to the organs internal processes as well as the standard defined physical processes such as fluid flow, heat flow and the other processes that are common to a description of fluids. The elements added to the system would then allow us to achieve a feed back system that we

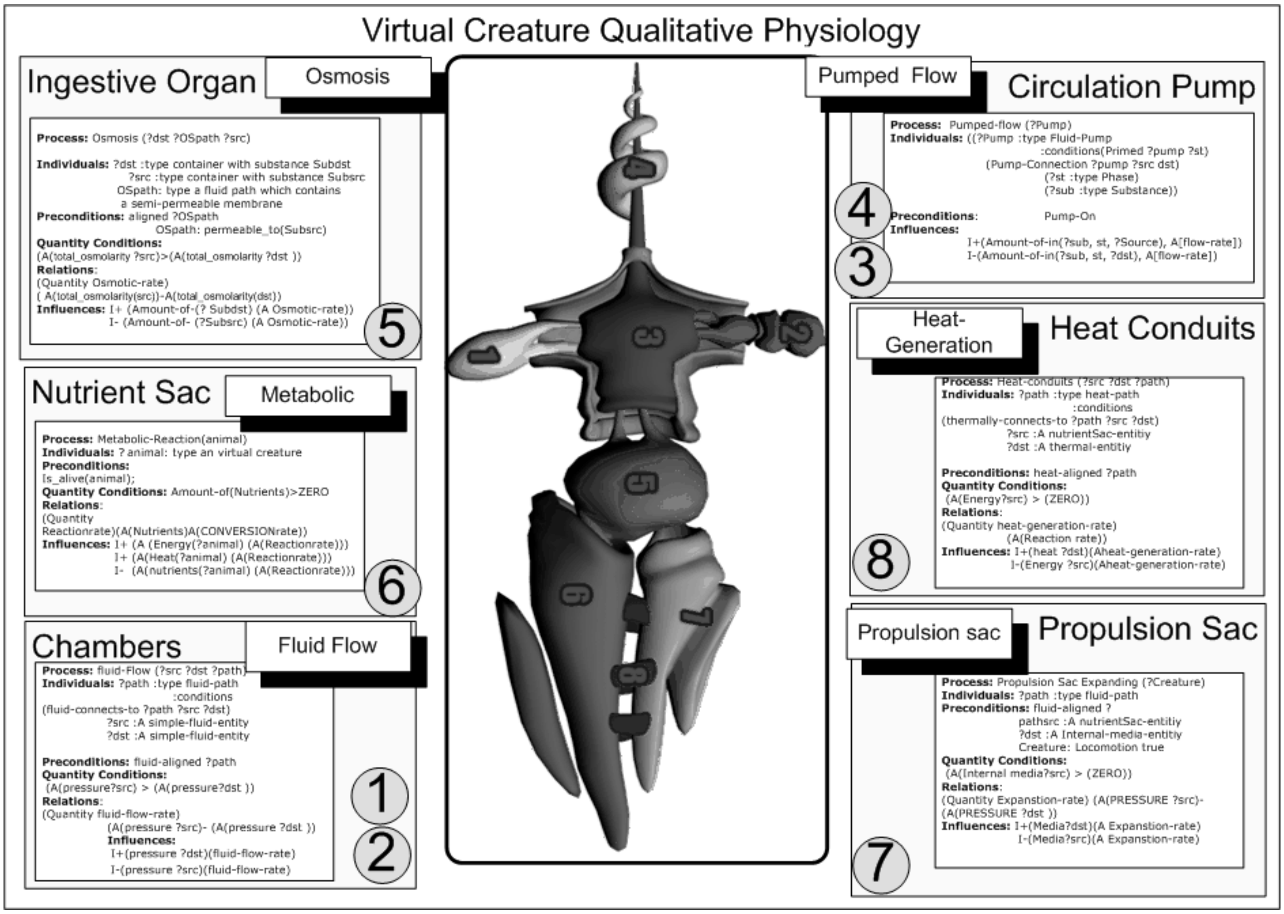

Figure 4: Overview of the Creatures Physiology

have deemed to be necessary for the implementation of physiological processes.

Upon this basic structure, we then developed the processes for each organ that operated upon the transported bodily fluid. We devised a system where each organ presented the system with a defined purpose and representation. For instance, the bodily fluid contains nutrients, which the creature requires for its metabolic processes, to acquire it an organ labelled "ingestive sac" was given the semi-permeable property that allows it to participate in the osmosis process. The semi-permeable property allows the creature to obtain nutrients from the volume that it is currently occupying. In this way we began our aggregation of the physiological processes of the creature, and laid the basis for its interaction with the external environment. We repeated this process of identifying organs and the physiological functions until we had achieved a system for which the creature, which demonstrates a homeostatic behaviour. This system is represented in the figure 4: Overview of the creature and depicts the organs and the common processes, which operated on them to form the resting state.

The creature its self thus operates from a basis of 12 processes namely: osmosis, heat flow, fluid flow, mixing, metabolic process, heat sac process, propulsion sac expansion, propulsion sac contraction, thermal control, pumped flow, propulsion control, sac control and sea media path.

3.2 Implementation for Qualitative Simulation of the Environment

The most basic of the entities defined in the domain is the material object. The material object defines the basic physical properties for a substance; for instance heat, conductivity, volume, pressure etc. Using this as a basic construct we have defined entities within the 3D environment using our scripting syntax to represent the common properties of the environment. Such as the volume entity which has physical properties which are the basis for the environmental processes and interactions. The physical properties of the volume derive from the fluid entity like the vital fluid.

The fluid environment for the virtual creature is created from an equal subdivision of the 3D space. Each volume being represented by a series of parameters for the physical fluid sea media. The difference in the parameters' values gives continuous processes for flows and convection currents in the environment. The visualisation for these processes must not only show the object but adequately display the active processes behaviour. These visualisations relate the visual phenomena within the virtual worlds and are there to provide insight into the environments activity and state. For instance a volume may enter a perturbed state in which the volume is out of balance with the rest of the environment. This new state acts to restore the equilibrium through a process other than convection. Thus to show the new state and the level of vortex process activity we spawn a vortex object whose size displays the process activity. In the diagram below, we show the relations we have derived for the qualitative variables and their associated visualization. For instance, we have chosen to depict the concentration for the nutrients by using a particle emitter. In a single line equation we depict this relation as:

$$\text{Particle Emitter-Rate} \;\alpha\; \text{Amount(Molarities-Nutrients)}$$

This description adequately fulfils the purpose of depicting for a volume entity its concentration in various substances. We can also use this method to describe the active processes within a volume these are shown in Figure 5: Environment Visualisation Overview.

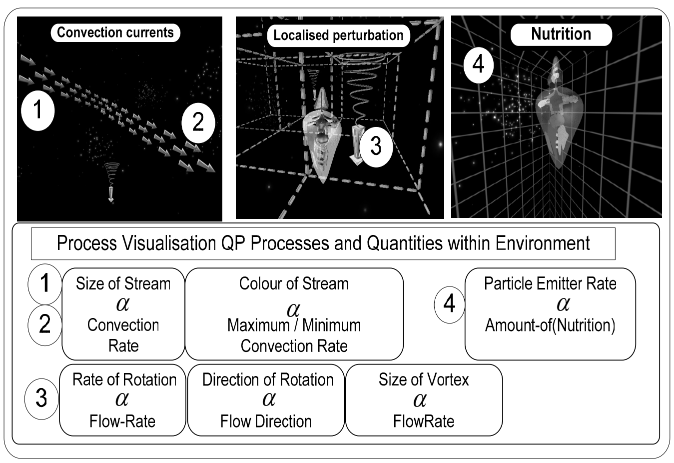

Figure 5: Environment Visualisation Overview

4 Results

The integration of the qualitative physiology in to the simulation for the environment has given us a unique avenue of investigation which allows us to develop experiments in the virtual ecosystem. This allows the simulation processes to be altered to determine the survivability of the creature as a function of its physiology. A number of processes are active between the creature and its environment when the creature is in the normal resting state producing the required homeostasis. We have implemented a first prototype of the system in which we have a basic set of physiological and environmental processes. This basis allows us to alter the simulation of, and experiment with the creature and environment. In this section, we illustrate the system behaviour by describing some specific results from the simulation.

4.1 The "Free Floating" Scenario

The behaviour of the creature in a non-agitated free-floating scenario shows the normal operation of its organ systems. Its physiological behaviour corresponds overall to the preservation of homeostasis against the influences of the environment. In addition to these processes, an active heat flow and fluid flow processes exist between the creature and the environment, which continuously refreshes the internal media with nutrients and deprives the creature of heat respectively. The creature's internal organs interact with this internal media.

In our development of the artificial creature, we have started with a representation of an organ and determined behaviour for it. We began by creating each organ as a series of containers that operate by using the vital fluid, which is circulated to them. Then each organs special properties then devised by giving the special properties to the container. For Instance, the heat conduits use the creatures' stored energy during the creatures locomotion cycle to produce jets of sea-media that propel it along.

The primary organs and their behaviour and processes are detailed in the Figure 4: whilst below we show the cycle for an element of vital fluid.

The vital fluid begins in the organ left chamber, this organ is the target for the pump thus it expands and contracts as the vital fluid enters and exits the organ. The right chamber is connected via fluid path to nutrient sac so a flow occurs between the two organs allowing the transfer of the vital fluid. The purpose of the nutrient sac is a metabolic one as it acts to decrease the concentration of nutrition within the vital fluid for the organ and increase the stored energy and heat for the creature. The depleted vital fluid is carried to the heat conduits organ, which is inactive in the free-floating scenario, and then to the ingestive sac. In the ingestive sac organ, the osmosis process occurs, this process describes the absorption of nutrients from the internal media into the vital fluid. The osmosis process occurs between the ingestion sac and the internal media as the organ has the semi-permeable membrane property and a connection exists between the two which allows the process to transfer nutrients to the vital fluid which is contained within the organ. The parameters for the vital fluid within the organ, concentration, molarity and mass are changed via the calculated resultant of influences from the active osmosis process, the active mixing process and from the active fluid flow processes which are transporting the vital fluid to the right chamber and from the heat conduits organs as depicted in Figure 6. The product of which is an increase in the concentration within the organ.

This organ thus enriches the vital fluid that is transferred via a fluid flow to the right chamber, which like the left chamber expands and contracts dependant upon the amount of vital fluid. So the enriched vital fluid is ready to be pumped to the left chamber to begin the cycle again. Also In this system, we have also the concurrent processes of mixing, which act to establish equilibrium between the different concentrations of nutrients, and heat flows, which the nutrient sac will generate from the metabolic process.

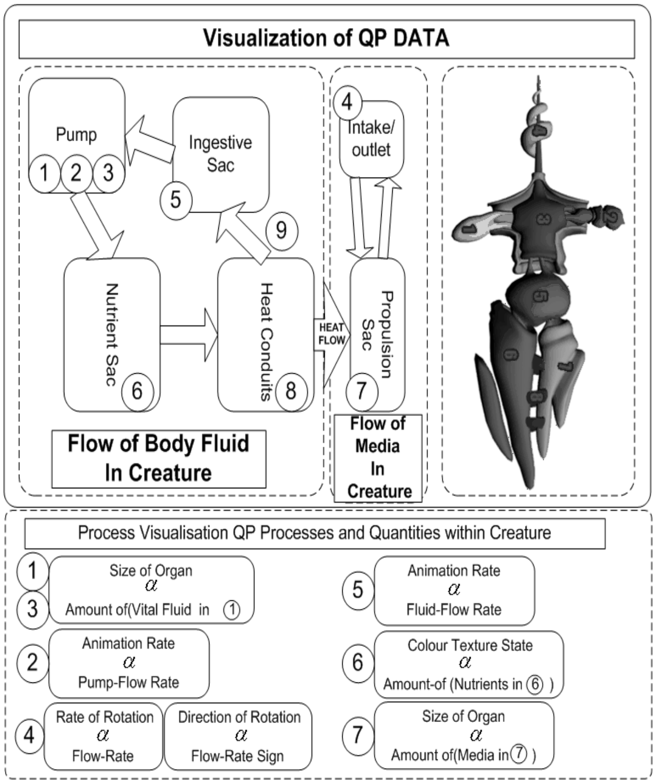

Figure 6: Qualitative Variables and their relation to Physiological Functions

In our system, the 3D representation of the organ may be altered to visualise states reached by the organ during simulation. For example, we have described the behaviour of the nutrient sac in terms of the process active within it, metabolic process. However, we can also ascribe a nutrient sensitive behaviour to the organ allowing concentration of nutrients to alter the colour states of the organ. To achieve this we have attached a series of qualitative limit point and landmarks. To generate the *QP_Effects*: `QP_Concentration_Min`, `QP_Concentration_Max` from limitpoints and the *QPeffect* `QP_Concentration_Update` has been assigned to a landmark.

The *QP_Effects* `QP_Concentration_Min` and `QP_Concentration_Max` are the minimum and maximum of the values which are used for the concentration of nutrients in the bodily fluid that are within the nutrient sac and are static values for the Organ. The values between these are communicated via the *QP_Effect*, `QP_Concentration_Update` which is a Qualitative landmark that may be given a function for the calculation of its future values via an Update Script similar to the relation scripts. In this way we can create a colour response profile for the organ. The Concentration of the nutrient within the sac is dependant upon the value of the physiological processes and their associated influence equations. These equations ultimately control the response of the organ. The application of these *QP_Effects* are shown in Figure 7.

In the free floating scenario, the creature drifts along with the motion of the sea-media in the environment and does not control its own motion and it is considered to be in an the energy conservation mode. The active processes in this individual view state for the creature are: the pumped flow, the fluid flow, the osmosis process, the metabolic process, the mixing processes, sac control and the thermal regulation which work upon the organs parameters of heat, temperature, pressure, concentration, molarity, volume, and conductivity to give a balanced solution between the internal physiological processes and the environmental processes such as heat flow and sea media flow which primarily rob the organism of heat and provide the path for the refreshment of the internal media.

The creature has its own system for propulsion, in which the organ states change, and the creature expends its internal energy; this system is described next.

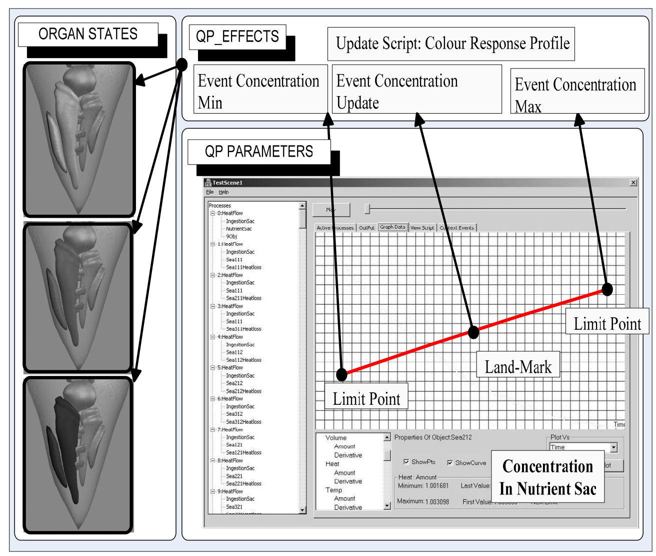

Figure 7: Evolution of the Nutrition Sac during Simulation

4.2 The Locomotion Scenario

The integrated approach to the simulation has allowed us to develop simulation effects for the environment as well as for the creature, which has allowed the triggering of different individual view states for the creature dependant upon the conditions that are prevalent in the environment. The major individual view states for the creature describe its locomotion state. In the individual view for the locomotion the *QPState* for the creature changes. This alteration in the

QPState determines which of the scripts are executed. It also alters the creature's parameters and which of the processes become active. The *QPStates* change the relations between parameters when the individual view changes. For example, in the non-locomotion states the circulatory pump rate is constant and its value does not change. However, in this new individual view the pump entities parameter, pump-rate, becomes dependant upon the parameter stored energy. Since the pumped flow process depends upon this qualitative parameter, the circulation rate of vital fluid around the system (whose fluid flow processes depend upon the transfer of fluid) also increase. The pump rate increases toward its maximum the further the amount of stored energy deviates from its maximum with the consumption of the energy by the heating conduits process which is activated by the individual view. Along with this change in pump-rate, the metabolic process, which is active in the nutrient sac, is also affected as in its relations its rate depends upon the qualitative variable conversion rate, which is a property of the nutrient sac that is increased in the individual view. Thus, the main effect of the new individual view is to activate the propulsion sac and the heat conduits processes and to alter the entities attributes and parameters allowing the processes to occur faster.

The heat conduits and the propulsion sac organs comprise the locomotive system for the creature and their processes heat fluid for expulsion/propulsion and manage the system of valves for the organ respectively.

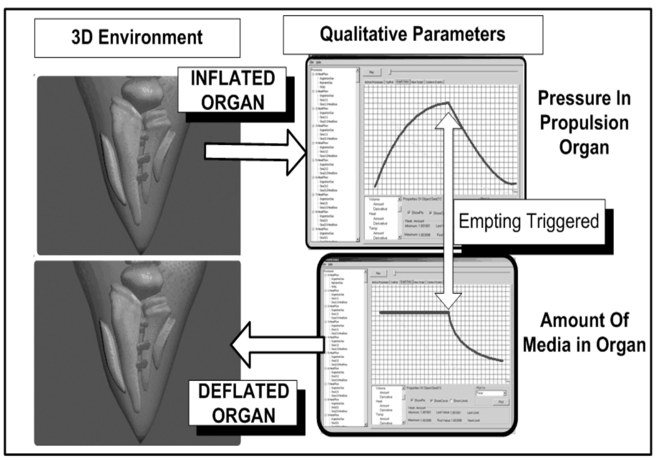

Figure 8: Variation of Pressure in the Creature's Propulsion System

During the Locomotion state the flow of sea media due to the pumping operation of the intake/outlet organ 4, which replenishes the nutrients within the shell of the creature from the environment, stops and is replace by propulsive thrusts from the propulsion sac.

In the locomotion state the sea-media that is within the shell is drawn into the Propulsion Sac organ 7 via a valve on the organ. This valve is controlled by the propulsion sac expansion process which sends the effect `QP_Effect_Fill_Propulsion_Sac` to begin the manipulation of the propulsion organ. The Sac closes the valve when full and activates the Heat Conduits organ 8 that heats the sea media which makes the pressure increase inside the sac. When the pressure inside the propulsion Sac passes a value it triggers the pressure valve on the sac and the sea media is expelled from the Sac via the propulsion sac contraction process. This process sends the *QP_Effect* `QP_Effect_Empty_Propulsion_Sac`, to the Unreal engine, which changes the *QPState* for the heat sac to empting. The shell expels the sea media into the environment creating a propulsion thrust and triggering a particle effect whose rate depends upon the rate of the fluid flow. The figure 8 depicts these changes in the creature with a plot of the pressure within the organ.

Spatially distributed volumes are used to describe the environment. A nutrient rich (*active*) volume contains a high concentration of nutrients and thus we have chosen to represent an attractive volume within the environment with a distinctive effect. This is achieved by generating the *QP Effect* `Start_Nutrition` when the *volume* enters this *QPState.* This effect relates the parameter "concentration" within the *volume* to the lifetime of the particle within the 3D environment. This creates the effect of a denser cloud of particles for higher values of concentration. Also within this *QPState* as the value evolves through the effects of convection processes a Update_Nutrition *QP_Effect* is generated for appreciable changes (~10% Saturation value). Each volume contains an imaginary media whose properties are devised to react to give thermo-mechanical effects. The vortex is a product of this effect and is created by a combination of effects upon a sea-volume. If the nutrient concentration of the volume decreases below a certain threshold and the rate of the convection current is low then the vortex will form. The processes which are active upon the volume when this occurs are: the convection process, the fluid process with the artificial creature and the thermal mixing process are all active within the Creature. This leads to scenarios in which the creature can find patches of high concentration of nutrients but by its presence cause instability in the volume, though the thermo-mechanical properties of the volume. This property creates a vortex that drives the creature, either by its effects or by locomotion, if the creature has stored energy, from the volume.

Conclusion

Our efforts to create an integrated approach to world and physiology qualitative simulation have produced an enticing opportunity to experiment with artificial life in a way that effects both the environment and the virtual creature simultaneously. This approach has been defined to give the modeller a method of affecting the creature and environment. A main benefit of this has been to propagate a change in the environment into the physiology for the creature allowing the creature to adapt a new homeostatic state. Future work in this area will include the expansion of the creatures' perception of the environment and interaction between creatures. For the environment the expansion of the states of the volume to allow for different "cloud formations" for the nutrients instead of the single particle emitter which we are using.

Acknowledgements

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