

Experiencing Belugas: Action Selection for an Interactive Aquarium Exhibit

Steve DiPaola
Simon Fraser University
steve@dipaola.org

Caitlin Akai
Simon Fraser University
cakai@sfu.ca

Bill Kraus
Digital Biology
bkraus@digitalbiology.com

Abstract:

This paper presents a case study of an action selection system designed with adaptive techniques to create a virtual beluga aquarium exhibit. The beluga interactive exhibit uses a realistic 3D simulation system that allows the virtual belugas, in a natural pod context, to learn and alter their behavior based on contextual visitor interaction. Ethogram information on beluga behavior was incorporated into the simulation, which uses physically based systems for natural whale locomotion and water, artificial intelligence systems including modified neural networks and a reactive hierarchical action selection mechanism to simulate real-time natural individual beluga and group behavior. The beluga's behavioral system consists of two layers: a low-level navigation system and a high-level reaction hierarchical action selection system. The system is designed to be run on consumer level hardware while maintaining real-time speeds.

Keywords: artificial life, collaborative interfaces, action selection, exhibit design, intelligent systems, neural nets

1 Introduction

Informal learning institutions like museums, science centres and aquaria are increasingly using technology to leverage traditional approaches to exhibit design and to provide more engaging and informative experiences for their visitors. Intelligent systems, such as those using action selection mechanisms, can satisfy this new interest in technology by providing flexible and adaptive systems. The increasing sophistication of action selection systems provides an opportunity to better engage visitors in immersive learning experiences by using information from global and local sources. A significant advantage of using adaptive systems with high quality graphics in exhibits is that they allow for responsive and dynamic interaction in a very short period of time. For institutions with high traffic, adaptive systems can be designed to support a collaborative and participatory space that could allow visitors currently interacting with the

system to informally and effortlessly pass on knowledge to new visitors, allowing them to access deeper content more quickly. Content can also be layered to support various learning styles and interest levels (Economou, 1998), which can encourage exploration through the use of 'what-if' scenarios as well as developing problem-solving skills (Adams & Moussouri, 2002). Presenting sophisticated educational messages at short, medium and prolonged/repeated time periods can lead the user to more substantial levels of content. Multimedia interactive exhibits can also incorporate personalization that allows visitors to work at their own pace, be in control of their experience and have specific questions answered. They can also be tied directly to curriculum content, which can be easily updated as curriculums change. This ease of updating allows institutions to use the same hardware while changing the content on a regular basis, which can encourage repeat visits.

This paper will present a case study of an action selection system developed as an interactive virtual beluga exhibit for the Vancouver Aquarium. We provide the background of the project, a description of the system, and present lessons learnt throughout the project.

1.1 Virtual Beluga Background & Objectives

The Vancouver Aquarium has over one million visitors annually, includes a significant marine science research center and promotes a strong educational mandate. As the largest aquarium in Canada, the Vancouver Aquarium is known for its innovative science-based exhibition and gallery design, and is interested in continuing to innovate in this area as part of its expansion process.

The Virtual Beluga project was commissioned by the Vancouver Aquarium based on our artificially-intelligent animal simulation software Digital Biology. Digital Biology is computer

animation/simulation software for creating real-time, photo-realistic interactive simulations of biological phenomena (Kraus, 2003). The aquarium was interested in using the system to build an exhibit around belugas. They currently have a number of live belugas as their main attraction and wanted to supplement this with a simulation of a virtual wild beluga pod. The aquarium also wanted to present their current research on beluga behavior and vocalizations (Vergara & Barrett-Lennard, 2003) in a way that was not possible with the live belugas. Beluga data was made available in the form of a beluga ethogram (Appendix A) (a comprehensive outline of beluga behavior), recordings of beluga vocalizations, and video footage of beluga behavior. The goal was to allow for a knowledge flow from the scientist to the staff to exhibit designer, and finally to the visitor through the exhibit. As new research was conducted in-house, it could be incorporated into the exhibit.

The exhibit had three main educational messages to promote:

- Belugas live in an acoustic world.
- Human activities affect how belugas use sound to communicate and navigate.
- Our knowledge of wild beluga behavior is very limited.

These educational messages required sound to be an essential component of the exhibit. Vocalization data on wild belugas is difficult to capture, and it is only through the study of captive belugas that so much has been learnt about beluga vocalization. However, behavior and vocalizations of captive belugas are not necessarily predictive of wild belugas, and the exhibit must be presented so that visitors are aware that it represents our 'best educated guess' of what beluga interaction might look like in the wild. In order to promote a respectful and appropriate relationship between the animals (even virtual ones) and the visitors, the aquarium impressed the importance of not letting visitors directly manipulate the virtual belugas. The use of an action selection system allowed for this type of indirect interaction.

Based on visitor studies, the learning objectives, guidelines and client recommendations, it was determined that the interaction design would

include a camera-tracked tabletop interface to allow for collaboration and to remove any expensive electronics from direct user contact. Visitors would have access to pieces representing either belugas or other environmental variables such as ice, food, or ships that they could place on the table. When they are placed on the table, they are tracked by the camera and introduced into the virtual scene that is projected on a large screen in front of the table. Because the system uses an action-selection mechanism, the belugas react to different environmental variables in different ways. For example, if an aggressive beluga is introduced into the scene, the other belugas will react to his aggressive behavior. Visitors will be able to try different combinations of variables in 'what-if' scenarios to find out how the belugas will react.

Using our design research process (DiPaola & Akai, 2006), and based on our studies of the aquarium visitors, we worked with the aquarium's educational staff to decide on overall and specific learning outcomes. Based on the learning outcomes, we determined a subset of behaviors to implement for the exhibit. We then looked at the categorized video clips of the real beluga behaviors and designed individual behaviors to match the belugas' movements using our biomechanics research. Our design process was iterative and continually incorporated feedback from scientist, trainers (who spend hours a day with the live belugas) and the educational staff. Once satisfied with a set of behaviors, our next step was to determine the context, i.e. what would generate a behavior based on the internal state and the ethogram. For instance, for each behavior we would decide on its internal state, whether it needed some precursor behavior, and what the beluga was likely to do afterward.

Considerable work was done on the task of simulating or emulating the beluga biomechanics – i.e. the natural swimming motion of the animal. While there is a substantial amount of research on dolphin biomechanics (Lang, 1966; Hertel, 1969; Fish, 1993; Long, Pabst, Shepard, & McLellan, 1996), there is much less on belugas (Fish, 1998; Fish, 2000). Nevertheless, biomechanical research has demonstrated that cetaceans like dolphins and belugas use a lift based propulsion system,

although swimming performance varies and was found to be correlated to morphological and ecological factors (Fish, 1998), Our simulation system supports both drag-based and lift-based physics systems. A drag-based system uses resistance, allowing the animal to simply push against the water to propel itself. A lift-based system, like that used by an airplane wing, takes advantage of the pressure differential on between the sides of the airfoil (or hydrofoil) to generate lift. The belugas in our simulation use a lift-based system to generate the forces required to propel themselves through the environment. Specifically, to generate the ‘lift’ required to propel itself forward, the artificial belugas need to alter the plane of their tail fluke within the tail stroke much as real belugas do. Simply moving the tail up and down will not generate forward thrust. Thus, movement was not ‘faked’, but corresponded to real world physics resulting in accurate and realistic movement.



Figure 1: Belugas at play: Screenshot from the Virtual Beluga simulation where belugas are interacting with each other and the test object (a floating ball). All of them are influenced by a virtual physics model and guided by collision detection.

2 Simulation System Overview

The Virtual Beluga system (Figure 1) uses techniques from advanced gaming systems, such as physically-based animation, real-time photo-realistic rendering, and artificial intelligence. The system also takes advantage of high-end consumer 3D graphics hardware allowing it to be run on affordable desktop computers without the need for expensive, specialized hardware or costly IT

maintenance procedures and expertise. It allows for:

- Real-time interaction among organisms as well as between organisms and the viewer (interaction system).
- Lifelike organic movement through the use of actuators ('virtual bones and muscles') and a virtual physics model (Figure 3).
- Intelligent behavior, in which some animals have the ability to learn from experience.
- A true 3D environment with collision detection; realistic objects, lighting and shadows as well as directional sound.
- Scalability, the number and complexity of organisms is limited only by the speed and memory of the computer on which it runs.
- Individual organisms can grow and change over time, and new organisms can be added and removed.

The artificial intelligence subsystem, which includes a feed-forward neural net, is built to allow for new behaviors with an action selection mechanism that chooses the appropriate behavior depending on the current context and the internal state of the animal. Specifically, the action selection mechanism enables an artificial animal to choose the most appropriate action from a repertoire of possible actions at any given time.

Our action selection methodology (Figure 3) uses a reactive hierarchical approach (Hendriks-Jansen, 1996; Bryson, 2000) where low-level actions such as individual body movements (e.g. fluke position) are used as the building blocks for mid level sub-systems (e.g. move from point A to B or keep a reasonable distance from others while staying in the pod). These mid level sub-systems are in turn combined with high level directed behaviors (e.g. I am hungry and need find my mother to nurse). In the Virtual Beluga model, the low level actions, which allow for natural looking movement, are:

- Paddle: Right, Left, Forward, Reverse
- Roll Right, Roll Left
- Body Pitch Up, Body Pitch Down
- Head: Yaw and Pitch

- Jaw Open
- Fluke: Frequency, Amplitude, Magnitude, Phase
- Fin: Yaw, Pitch, Roll, Frequency

Each animal is equipped with sensors used to detect other animals, objects in the environment, or user interaction (Figure 2). Information from these sensors, combined with the animal's internal state (e.g. level of hunger, fear, current position, family status) and memory of previous events, is used by the animal's action-selection mechanism to choose an appropriate behavior. These animals are autonomous entities, so when combined with stimuli and each other, they create non-deterministic and natural group scenarios.

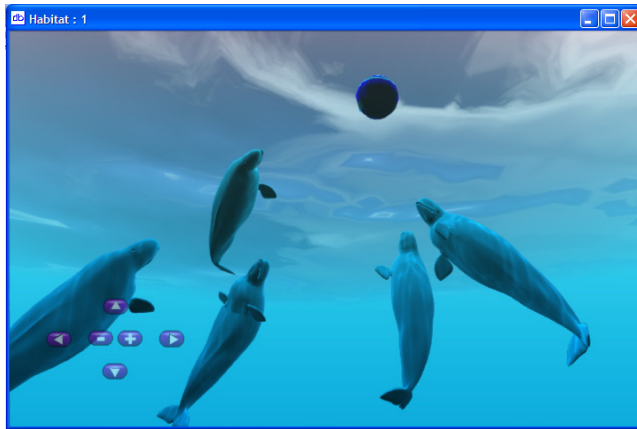


Figure 2: Screenshot of Virtual Beluga exhibit where the belugas are swimming around the user controlled test ball as they interact with each other.

Our system was originally inspired by the work of Tu (1999) and Tu & Terzopoulos (1994), which used an action selection mechanism based on an internal state to generate behaviors for artificial fish. In this system, natural movement was achieved through mesh deformation using a network of virtual springs. Our system uses a hierarchical node structure, where each node controls a set of vertices. This is type of system is typical of advanced gaming systems that incorporate physically based models (Brown et al., 2001).

3 The Behavior System

The virtual animals in our interactive simulation system have a behavioral system consisting of two layers (Figure 3): a low level navigational system

which uses a neural net, and a high level, reactive, hierarchical action selection system.

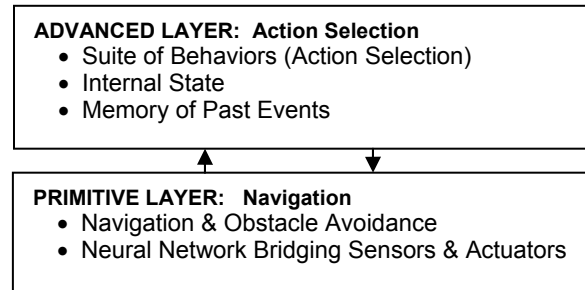


Figure 3: Two Layer Adaptive Behavior system with action selection on the top layer and navigation/avoidance on the lower.

3.1 The Primitive Layer: Navigation

At the lowest layer of the system is a navigational system responsible for directed movement and obstacle avoidance. This primary layer is conceptually similar to systems described by Renault, Thalmann, and Thalmann (1990) and more recently Lozano and Molina (2002), although it includes a multi-layered feed-forward neural net system which is closely coupled with the control of node based deformable 3D mesh models. The neural network collects input from a series of sensors and the output specifies the desired speed and orientation (yaw, pitch, and roll) at each time step (Figure 4). The output information is then used to specify the positions and orientations of the nodes that control the actuators responsible for movement. The neural net system is designed by hand via a custom design tool which allows for multiple middle layers which can use min/max, step, or sigmoidal node functions.

The sensor system is implemented with a series of equally spaced 3-dimensional arcs projecting from the beluga's head into the environment. As the animal moves through its environment (or alternatively as other objects move into range), a sensor or group of sensors are tripped when an object intersects with the arc associated with those sensor rays. The size of the signal generated depends on the closeness of the intersecting object. The range of a sensor also depends on the speed of the animal – as an animal increases speed, it can sense objects farther in front of it.

The neural net has 11 inputs: 9 sensory rays that together make up the 3-dimensional arcs from the animal's head and two target direction parameters for yaw and pitch (Figure 4). While the Advanced Layer gives the animal its desired target direction, the neural net vision and navigation system can adjust that target direction and speed based on sensory and collision closeness input of the 9 sensory rays, allowing the animal to adjust that direction and speed to avoid and naturally navigate around an object, via its 3 outputs (speed, adjusted pitch and adjusted yaw).

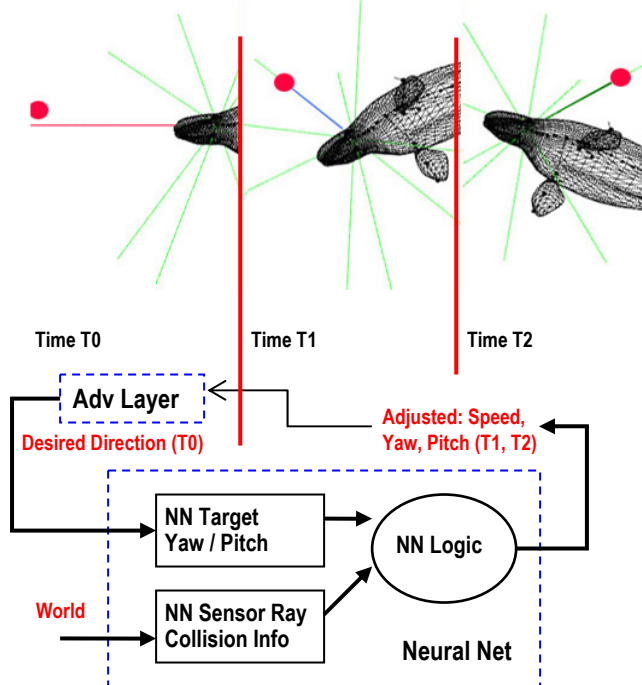


Figure 4: The beluga's neural net (NN) input has 9 sensory rays plus target yaw/pitch. The Advanced Layer's desired direction can be adjusted by the NN, based on ray collision and distance, where it sees the red ball at time T0, slows down/avoids it at time T1 and naturally banks around it at time T2.

Each node of the actuator system is essentially a joint, having a specific speed and range of motion. Nodes can be hinge, ball-and-socket, or fixed joints. Because the node system is hierarchical, a change in the orientation of a given node will result in a change in all sub nodes. In addition, since each node controls the movement and position of a section of the mesh that makes up the animal, movement of a node will potentially create a simulated physical force, which can be used to propel or modify the movement of the animal. For example, if a beluga is swimming

forward and there is an iceberg slightly off to its right, sensors on the right side of the animal will be triggered, and the neural net will calculate a course setting yaw to the left (see Figure 4). This information will then be used by the actuator system to adjust the trunk of the animal to pitch downwards while at the same time altering the position of the flippers to create a drag-based torque on the animal. The result is that the beluga will roll on its right side and turn to the left, much as a real beluga would do, as seen in Figure 4 where the beluga first steers away but then around the red obstacle ball. As the animal changes its orientation, the iceberg is no longer in front so the sensor is no longer tripped, and the beluga begins to swim in a straight line again or resume its previous behavior as dictated by higher functions of the Advanced Layer.

3.2 The Advanced Layer: Goal Arbitration

While the navigational system can handle obstacle avoidance, directed movement depends on goals set by the high-level action selection layer. At each step in the simulation, this layer is responsible for choosing the appropriate goal-directed behavior based on the suite of available behaviors, the internal state of the animal, and the current environmental context. Goals may be achieved through the navigational system (e.g. swim towards food), or not (e.g. perform a stereotypical threat display). In other words, the advanced layer determines the current goal of the system, and the navigation system provides one means of accomplishing this goal. Both the internal state and the potential behavioral repertoire can and do vary with the type of animal, its age, its sex and the individual experience of the animal. Different animals can have different behaviors to choose from, and the likelihood of choosing a particular behavior will vary. For example, two males might have the same set of behaviors available but make different choices due to differences in their particular social status, or level of aggressiveness. Since the system also supports memory, past events can also modify the likelihood that the action selection mechanism will choose a particular behavior in any given context.

3.2.1 Internal State and Memory

The action selection mechanism and the internal state of an animal form a feedback loop in which the performance of behavior satisfies the internally driven need (negative feedback loop). For example, mating behavior, once completed, reduces the urge to mate. Similarly, successfully fleeing a predator reduces fear levels and makes it unlikely that the animal will continue fleeing. Conversely, if a chosen behavior does not satisfy a need, it may result in an escalation of behavior. For example, if a low level threat display does not cause a rival to disengage and therefore does not reduce aggressiveness, a more aggressive threat may be chosen.

The other internal state component is a memory queue, a first in - first out (FIFO) queue, which holds a memory of recent events. Memory affects both the internal state and the action selection mechanism. The animal's memory has a decay, so

if a particular behavior is performed the animal is less likely to perform that behavior again (it has a lower priority) until after a certain time period. For example, by completing the courtship behavior the mating urge is reduced and the urge needs to build up again over time. However it is possible to have a need that is never satisfied and in that case a delay or decay can occur with an associated behavior, causing that behavior not to start again till some time is passed. The animal's drives, which are single parameter values, can include their sex drive, fear, hunger, and aggression. A more explicit form of memory is used by the animal to keep a tally of the individuals it has interacted with. If an individual recently interacted with animal x, and had a successful or friendly interaction, that animal is more likely, if given a choice of individuals to interact with, to interact with animal x in the future. Figure 5 describes the advanced layer in more detail.

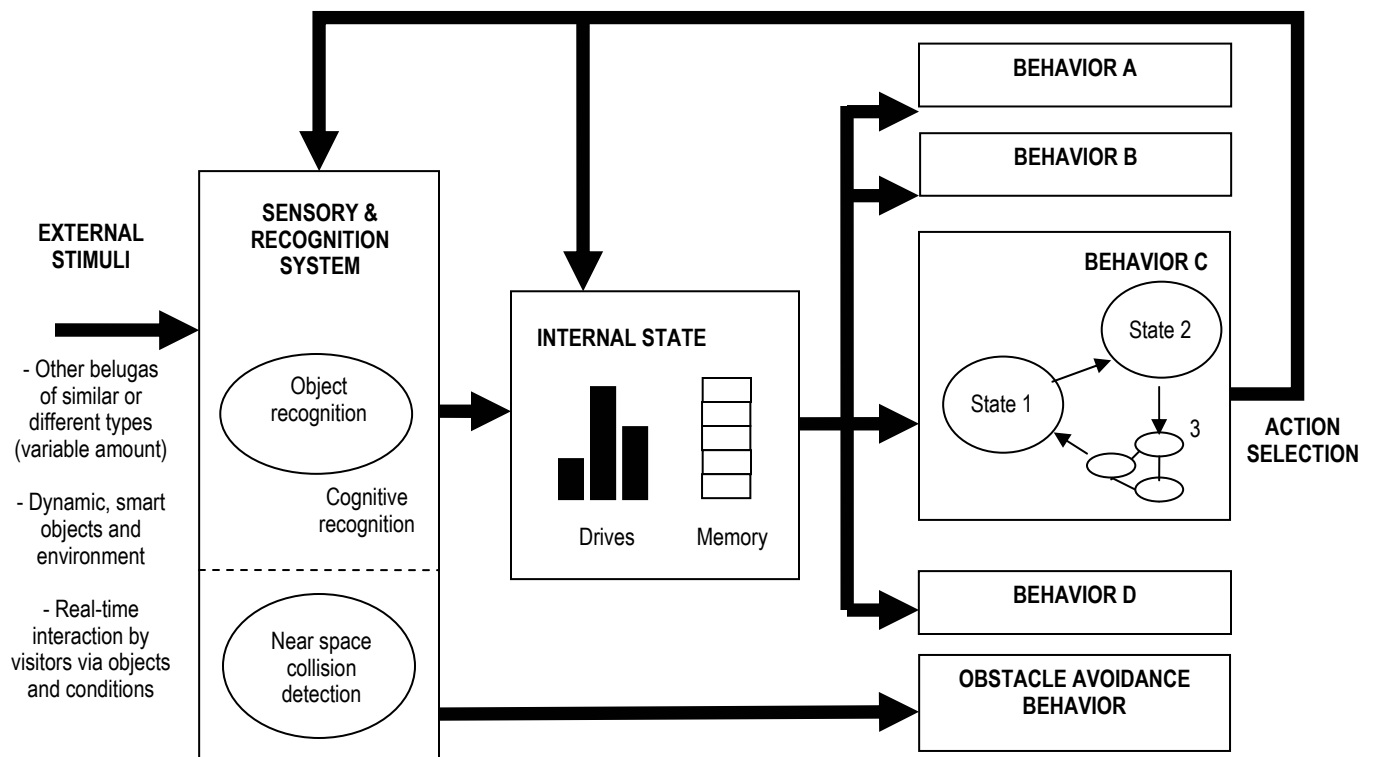


Figure 5: The advanced layer: action selection process diagram.

3.2.2 Action Selection Process

As with other reactive systems (Hendriks-Jansen, 1996; Bryson, 2000) the system attempts to quickly react to a complex, dynamic environment (which in our case includes other whales of the same and differing types, dynamic objects and environment and real-time visitor interaction) using the internal state of the agent. The behavior that is chosen from the action selection mechanism (ASM) depends on the animal's current internal state and memory. If the animal is hungry, the ASM is more likely to pick a behavior to look for food, or if the animal has food in sight, to pursue it, capture it and eat it. Selection is done by polling all available behaviors to determine the behavior with the highest priority to be performed. This priority is in turn determined by the behavior itself, based on the internal state of the animal. So all things being equal, the internal state will alter the intrinsic priorities of available behaviors, determining which behavior the ASM chooses for the animal to perform. Once a behavior has started, for example, behavior C in Figure 5, it evokes a finite state machine (FSM) for that behavior and continues with that behavior automatically to completion unless it is preempted by a behavior with a higher priority. If the animal performs a behavior to completion, the presumption is that it will satisfy a drive or a need and therefore the behavior is less likely to be performed again in the near future.

As shown in Figure 5's behavior C, a behavior's FSM can be linear or non linear, and a sub-behavior can itself be a FSM – in this sense, a given behavior can be composed of a hierarchy of FSM.

The structure of the ASM, from the interrelationship of the behaviors, that represents a sub-component behavior, and the relationship between the internal state and the ASM, is informed by the ethogram created initially by the aquarium scientists. Our modified and collaborative ethogram has become the main design and communication document between the aquarium scientists and our research team. Tyrrell (1993) and more recently Blumberg (1994) have noted the difficulty of applying behavioral models

to the problem of modeling action selection in virtual animals whose behavior mirrors that of real animals. Our case is slightly more severe, in that our interactive system will be situated next to real world belugas. The ethogram, the video footage, the sound recordings and scientific findings that informed our system were based on these real belugas. More to the point, as we fully implement the interactive exhibit, (it is being used on more supervised aquarium camp trials as of this writing) visitors will be moving between the two exhibits with our more experiential interactive exhibit representing a wild version of a beluga pod on one side of the gallery, while the real belugas on the other side represent themselves and paradoxically their captive state. In effect, we are using the real world beluga information to openly pontificate on how wild belugas would act, and therefore bring regular visitors in to the thinking process of aquarium researchers.

3.3 Real-time Architecture and Graphics

Maintaining real-time speeds, allowing for user interaction and creating an open-ended simulation system require the system architecture to be set up in an efficient but organized way. At its core, the system maintains a tight Main Simulation Loop (MSL) which is executed once per frame. As is typical for real-time gaming and simulations system, a frame, occurs 30 times a second or faster, while reasonably continuous perception can be maintained as low as 15 frames per second.

The MSL consists of two steps (Figure 6). In Step 1, each animal is given the opportunity to sense its environment (i.e. objects, other individuals or user input) and react to it (1.1). Reactions can be either changes in internal state, changes in body position and shape, or both. Changes in body position and shape are accomplished through mesh deformation, in which the positions and orientations of the individual vertices that make up the mesh are altered (1.2). In some cases, the change in body position is a result of reactive physical forces, such as when the animal collides with a solid object. In other cases, the change in position and shape are proactive – where the animal explicitly modifies its body position and shape to affect the environment, such as

swimming movements. Step 1 is executed on the Central Processing Unit (CPU).

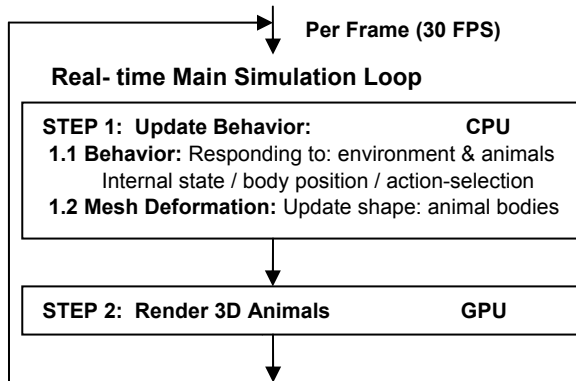


Figure 6: Architecture of internal Main Simulation Loop (MSL). Note that the behavior can be reactive (e.g. responding to physical system), or proactive (e.g. I want to go after that ball).

The second step of the MSL is the 3D rendering of the animals. This step is primarily executed on the Graphics Processing Unit (GPU) of the accelerated video card and is typically the most performance intensive. While the rendering in step 2 depends on the vertex positions calculated in step 1.2, the behavioral calculations of 1.1 for the next frame can proceed while the rendering in step 2 is taking place, improving efficiency. Also note that the simulation does not require step 2, and can proceed without being rendered.

Each animal in this underwater environment has a detailed texture (e.g. skin patterns and coloration, eyes, mouth), water caustic effects, a bump map and a shadow effect (which is created with a shadow map by rendering the scene from the light's point of view). The detailed texture map, the caustics, the bump map and the shadow map use all four texture units in the GPU processor. In the programmable shader, these four texture units are combined to create the final effect, which aims to achieve real-time photorealism.

The water surface and effects are a separate model. A Fast Fourier Transform (FFT) is used to compute the wave deformation of the water surface, which is computed on the CPU as in any other model. However, the transparency and reflection effects are accomplished through programmable shaders on the GPU. To create

photorealistic water effects (water surface as well as water volume) and render animals in real-time, it is necessary to take advantage of hardware acceleration by using programmable vertex shaders and fragment shaders as well as other GPU techniques. This is achieved by writing small shading programs or algorithms that are executed on the GPU at frame time. We use the Cg shader language (Mark, Glanville, & Akeley, 2003) for this task to keep the shader language less platform specific while guaranteeing maximum hardware acceleration. By using programmable shaders and leveraging both the CPU and GPU it is possible to maintain a level of real-time photorealism. Research has begun to show that as GPU's become more modular, it may be possible to move more processing, including behavioral processing, over to the GPU (Harris, Coombe, Scheuermann, & Lastra, 2002). We also take advantage of the parallelism by using the Intel Streaming Instruction set (SIMD - single instruction multiple data).

In the case of the low level neural nets, we have designed custom tools, so we can "hand design" a neural net for a specific animal. We have also developed tools to optimize the performance of these networks. Once coded, these tools are able to translate the designed neural net into highly optimized "C" code, which is incorporated into the system.

An extensible object oriented framework is used both for speed and modularity for the action selection mechanism and behaviors. Each animal type is encapsulated in its own dynamically linked library (DLL) which contains all its behaviors, and allows for easy extension and modification of behaviors. Adding a new behavior requires creating a new object and attaching it to the system, while modifying an existing behavior can be done without corrupting the larger system. The system is generic enough that each individual has information about itself that can be gleaned by other animals. The goal is to keep the system open enough that it is possible to mix and match different animals and modify their behaviors in a safe and open-ended way. The system allows a designer to take two different types of animals that may have never really encountered each other, for example a modern fish and a now

extinct prehistoric pelagic animal, and put them in an environment together.

4 Methodologies & Design Process

Building an exhibit around virtual intelligent belugas offered an opportunity to provide a unique visitor experience at the Vancouver Aquarium. We wanted the design to maximize the action selection behavior of the belugas by allowing for open-ended scenarios that let visitors explore the belugas and their habitat by adding/removing environmental variables and observing the belugas reactions. Our main design goal was to facilitate a process to create user-centric shared, collaborative and reflective learning spaces around smart multimedia interactives.

Adaptable systems allow for users (staff and visitors alike) to use the system in various ways allowing for unique opportunities and potential to emerge. This can occur when a system is made modular, allowing for repurposed or recombined use because the system is inherently open. Therefore the same basic modular system can be used on a simple computer/mouse setup in the summer camp, be under full control by an experienced volunteer member on a plasma screen in the interpretive center, and be used on the main exhibit floor with a fully collaborative tabletop and projection system. At the educational level, aquarium staff can play with open ended scenarios using the interactive exhibit, presenting a sequence of events or serial narratives with different educational directions; at the visitor level, the interactive can be vary depending on the group and the specific social setting.

Another adaptive technique that we have employed in our design and software process is to work in layers. The benefits of a layered approach in adaptive design have been well documented (Moran, 2002). Layers allow for flexibility between layers. Fast layers explore changes (originality) while slow layers constrain fast layers but provide continuity. A layered approach, be it with the action selection system we are using in the animal behavior software or in the conceptual design of the physical setup where interaction, collaborative discussion space and

display of the non-deterministic results are all separate layers, allows us to constantly incorporate new insights on the science, or user experience level.

The experience of designing an animal simulation system using an action-selection framework was quite different from a traditional software engineering project. The use of the neural net architecture and action selection mechanism allowed us to use an iterative design process that was not pre-defined after initial interviews with the aquarium, but was flexible and evolved at each iteration of system development. The effect of realism achieved through this process was so high that the head researcher at the aquarium commented that the simulation could be used as a tool for scientists to gain insight into whale behavior. While encouraging, this is both a benefit and a possible danger since the simulation represents only an 'educated' guess at what wild beluga behavior might look like. For example, our first rapid working prototype was of a swimming beluga where it was possible to interactively see internal anatomy -- an interactive, animated scientific illustration of sorts (Figure 7). Despite the potential educational value of this kind of illustration, a considerable amount of guesswork was involved in determining how the internal anatomy of a beluga might look while moving, making it a remarkable, but not necessarily accurate representation of beluga anatomy. It is particularly important to ensure that information is accurate or at least explicitly presented as conjecture to visitors when the exhibit goes onto the gallery floor. If the system is realistic enough to prompt beluga experts to see it as a source of information on beluga behavior, visitors are likely to make even greater assumptions. However, if presented with appropriate cautions, the system could serve as a test-bed for theories on wild beluga behavior.

One of our design goals was to facilitate an accurate and comfortable scientific knowledge flow from scientist to the software system through to viewers interacting with the exhibit. The first step was to better synchronize the language used by the marine mammal scientists to our adaptive behavior system. To do this we worked to maintain the parallels with the ethogram and our

work. In ethology there are various discussions of how to organize behavior with hierarchical approaches and animals as state machines. Set up correctly this can parallel an object oriented implementation of the simulation software, where hierarchical organization of behaviors and state machines exist as well. We tried to create a design approach that bound the scientific structure and our software research structure using adaptive design techniques. This approach was critical to achieve a real world learning exhibit using new and unfolding research areas, in a cost effective and time efficient way.

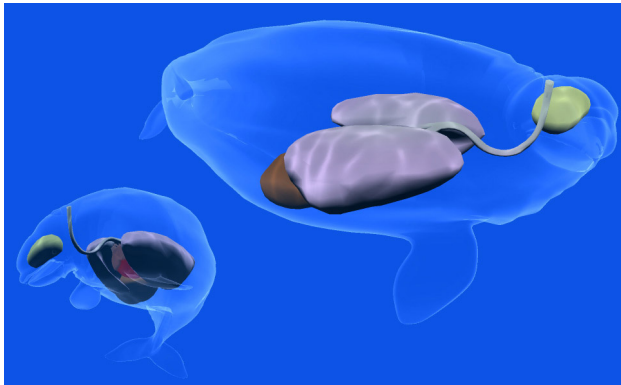


Figure 7: Screenshot of an early design direction of virtual belugas, allowing users to interactively toggle on different internal anatomy as the belugas interacts with its environment.

Unlike active learning action selection systems described by Blumberg, Todd, and Maes (1996), Humphrys (1997) and Bryson (2000), our system has no dynamic learning data structure. Therefore our system could not cope with new situations. The emergent complex behavior is a result of the animals interacting with each other, similar to a simulation game where the solutions are open-ended. The current version of the system can have any number of females, males and calves, all with different interacting behavior. Our research goals are to continue to streamline modularity for an adaptive and iterative design process, and document this approach with process flow recommendations and user studies verifying its usefulness.

5 Lessons Learned

We have learned several important lessons throughout this project that may be applicable to

similar action selection systems. Most of the lessons revolved around the flexibility and open-ended nature of an action-selection system. To summarize, we learned the following:

1. Working with beluga experts helped to ensure our system provided an accurate reflection of beluga physiology, behavior and movement and allowed for increased accuracy and realism.

We worked closely with the aquarium to ensure that the system faithfully represented beluga physiology and behavior. This required several iterations of development, and a longer design cycle, but resulted in a more realistic simulation. It also called for a more open-ended design process that evolved as the project progressed. The beluga ethogram developed by aquarium researchers was the key document used to develop a suite of behaviors for the virtual belugas. The ethogram, based on data collected at the aquarium provided a range of beluga behaviors to draw from.

2. The more realistic the simulation looks, the more people (experts and non-experts) will assume that it is a reflection of reality.

The simulation was realistic enough that it could influence even expert opinions on animal behavior. It is important to be aware of this when designing such systems and when possible attempt to control for it by relying on credible data and making clear any assumptions made in the simulation. This is important whether the system is being used simply as an exhibit or to test expert's hypotheses of what wild animal behavior might look like. For example because of the limited data available on wild beluga behavior, our simulation was based on data from captive belugas. During use of the system, it is explicit that we are making an educated guess at what wild beluga behavior looks like, and that data from captive belugas may not be a good reflection of the behavior of wild belugas.

3. The action selection system allowed for broader educational outcomes, and encouraged exploratory and collaborative behavior by visitors.

The flexibility provided by the system allowed for more open-ended educational outcomes. We were able to build broader educational objectives around the behaviors without making them explicit at the beginning of the process. This permitted a more exploratory approach to educational content and encouraged a collaborative approach to the design of the system.

4. The flexibility of the system allowed for adaptability to a multiple uses.

The beluga gallery at the aquarium sees multiple uses including: evening functions, school groups, summer camps, sleepovers, and regular visitor use. This requires that exhibits be adaptable to several different uses. The virtual beluga system is usable for multiple purposes because of its flexibility in design and open-ended educational content. It was meant to be accessible to a wide range of users, and can adapt to different uses, with very little effort.

5. Complexity of the ASM system and seeming emergent behavior has made us rethink the number of behaviors we need to implement for our specified learning outcomes.

Even in early iterations of the prototype system, as is true with most complex systems, we noticed that each new additional behavior caused "an almost combinatorial explosion in emergent behavior" (a quote from one of the zoologists). This is true because our system is highly complex with aggressive males, calves following their mothers, mothers trying to stay in a cohesive grouping, all with inter-related and conflicting interactions. On top of this complex social world, the system can dynamically change environmental scenarios and smart objects that deeply affect the behavior of the pod as well as real-time user (visitor) interaction via smart objects. This has made us rethink the number of behaviors we need for our learning objectives.

6 Conclusion

Our goal was to design a system that emulated the behavior of real animals, and was flexible enough

to work in a variety of situations. The system required that we draw from real research both from biomechanics (Fish, 1998; Fish, 2000) and ethological literature and from local research on the specific animals the system represented. We needed to build a flexible enough framework to emulate a non-deterministic simulation that allowed for adaptive use and adaptive educational techniques. As part of our work, we have found that this approach has the potential to then feed back into scientific research because it requires rigorousness and a test bed for how various behaviors fit together within an action selection environment.

Much of our research work has been to build a system and design process flexible enough for working directly with researchers and research data in an iterative way. There appears to be the potential to take this system and feed it back to researchers to allow them to test hypotheses on how these behaviors work. However the main goal has been to use adaptive design techniques mixed with adaptive behavioral software techniques to allow a knowledge flow from scientist to exhibit interactive to visitor that allows informal learners to engage more deeply in complex content.

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Appendix A: Beluga Ethogram

Table A1 shows the beluga ethogram developed by marine mammal zoologists based on data collected from live captive belugas at the aquarium. The ethogram document was one of the main communication tools to facilitate beluga behavior knowledge flow between the marine mammal zoologists and our research team.

Table A1

BELUGA ETHOGRAM	
LOCOMOTION	
ECHELON SWIM	Calf swims alongside adult, roughly parallel, or slightly staggered, maintaining its relative position to adult for at least 3 seconds. There is often contact, with the calf touching the adult's flank.
PIGGIBACK SWIM	A particular form of echelon swim in which the calf swims directly above and often slightly behind the adult, with its head right above the adult's dorsal mid line.
FOLLOW SWIM	Calf swims directly behind the adult, maintaining relative position for at least 3 seconds.
SWIMS IN FRONT	Calf swims in front of adult, maintaining relative position for at least 3 seconds
SWIMMING UNDER	Calf swims directly below an adult, and slightly behind, usually accompanied by bumping or nuzzling.
PARALLEL GLIDING	Two or more animals float or glide at surface, positioned parallel to one another --within 3 m.
SYNCHRONOUS SWIM	Three or more animals swim within 3 meters (roughly a beluga body length) of one another matching their speed and direction and maintaining their relative positions.
SPEED SWIM	A group of animals swims very rapidly in circles with vigorous movement of the tails. This swimming is visibly faster than normal, so the animal's skin looks wrinkled due to the friction with the water.
ADULT-CALF /AFFILIATIVE / PLAY/ NEUTRAL	
BUMP	Calf swims under adult, repeatedly raising & lowering its head, contacting mammary regions.
NUZZLE	Contact in which an animal slowly and gently brings its head into contact with another animals' body.
RUB	An extended form of contact in which the calf rubs part of its body against the adult. The calf approaches the recipient, & rubs most of the length of its body against the back or side of the recipient.
BARREL-ROLL	A quick succession of rolls on the horizontal plain, occurring while swimming. It looks playful. The calf used to do this when he was younger.
NURSING	The calf takes a teat in its mouth, and holds on. There is a reduction of swimming movements by the mother and distinctive rapid short tail motions by the calf, maintaining relative position to the mother.
SPYHOP	The animal assumes a vertical or oblique position in relation to the water surface, thrusting its head out of the water and maintaining that position while clearly watching its surroundings.
SPYWATCH	The animal clearly has one or both eyes above surface of water, usually while floating or gliding. This behavior is usually performed while watching the trainers or members of the public.
BUBBLEPLAY	An animal blows bubble rings and swims after them, displaying various playful behaviors such as poking its rostrum inside the rings until the ring brakes or "pops" with a noise.
HEAD STAND	An animal adopts a vertical position, head down, tail flukes above the surface, bobbing up & down.
COURTING/MATING	
PRESENTING	An animal turns on its side and presents its ventral side to another animal. It may be reciprocal. Often accompanied by bubble-streams from the blowhole.
COUPLING	It may follow after PRESENTING. The two animals rub their ventral sides together for a few seconds.
POSTURING	Similar to PRESENTING, but not directed at any particular individual. Often accompanied by up-down movements of the head, bubbling, and graded vocalizations.
SWIM TOGETHER	When two animals swim closely together, but not necessarily in synch, in between PRESENTING and/or COUPLING bouts.
RUB	An extended contact; the actor rubs the length of its body against the back, or side of the recipient.
AGGRESSION	
CHASE	An animal swims rapidly at another, who swims away from the actor.
JAW CLAP	An animal, while facing another, rapidly opens and then closes its mouth, producing a sharp sound which resembles a gun-shot. Sometimes the jaw clap is mutual.
HEAD THRUST	An animal, while facing another, moves its body quickly in the vertical plane, producing either an up and down or a down and up motion. HEAD THRUSTS, like JAW CLAPS, can be produced in rapid series.
OPEN MOUTH THREAT	An animal, while facing another, rapidly opens his or her mouth fully and holds it open for at least 1 s. Mutual open-mouth threats do occur.
DIRECTED LOOK	An animal swings its head laterally to point the rostrum at the recipient. This behaviour often involves a rapid re-orientation of the actor's whole body towards the recipient.
MELON EXTENSION	The actor, while facing the recipient, markedly changes the shape of its melon, forming it into a ball and

	pushing it forward.
HIT	Contact in which the actor rapidly & forcefully hits (with tail, side body or rostrum) the recipient's body.
BITE	A particular type of contact in which the actor opens its mouth fully and bites the recipient
BITE THREAT	The actor opens its mouth fully while facing the recipient and moves its head quickly towards the recipient but without making contact (slightly different than OPEN MOUTH THREAT above).
CHARGE	The actor swims at full speed directly at the recipient, traveling at least 3 m
RAKING	One or more animals scrape the length of the recipient's body with their teeth.
SUBMISSION	
FLINCH	An animal rapidly lowers its head & moves its whole body to face away from another (aggressor) animal.
FLEE	The recipient of an aggressive act rapidly swims away from the aggressor.
LOOK AWAY	An animal turns its head to look directly away from another
AVOID	An animal moves its whole or part of its body to avoid upcoming contact with another animal.

Author Biographies

Steve DiPaola

Steve DiPaola is an Associate Professor at Simon Fraser University where he directs the iViz research lab (ivizlab.sfu.ca) which incorporates intelligent cognitive and living system techniques within interactive visualization systems. He came to SFU from Stanford University and before that spent 10 years as a senior researcher at NYIT Computer Graphics Lab, an early pioneering lab in 3D and interactive techniques. He has also led research groups in industry including Electronic Arts, and Saatchi Innovation. Active as an artist, his work is shown internationally including the Smithsonian and Whitney Museum of Art. Address: Simon Fraser University, 10153 King George Highway, Surrey, BC V3T 2W1, Canada. E-mail: sdipaola@sfu.ca

Caitlin Akai

Caitlin Akai is a Master of Science Candidate at the School of Interactive Arts and Technology at Simon Fraser University, in British Columbia, Canada. She holds a Diploma in Computer Science and a Bachelor of Arts in Art History from the University of British Columbia. Address: Simon Fraser University, 10153 King George Highway, Surrey, BC V3T 2W1, Canada. E-mail: cakai@sfu.ca

Bill Kraus

Bill Kraus has a PhD in Evolutionary Biology, and currently works for NASA developing genetic programming software to create evolvable hardware. He is head of digitalbiology.com. Address: Digital Biology, 12335 Greenleaf Way, Truckee, CA, 96161. E-Mail: bkraus@digitalbiology.com