

Evolution of Virtual Catapults

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Abstract

We describe the re-implementation of a system to evolve the morphology and behavior of artificial creatures, originally due to Karl Sims. The new implementation is fast, flexible, and allows for the evolution of a range of novel behaviors not previously seen in Sims' or related work. In particular, we use off-the-shelf dynamics simulator engines that can be exchanged on the fly, and introduce a modular program structure that allows for the creation of interesting environments for adaptation—including depletable resources and other virtual creatures—as well as novel sensors, such as for color or smell. We describe the results of evolutionary experiments studying the diversity of throwing strategies of virtual catapults and the evolution of the projectiles.

Introduction

The evolution of morphology and behavior has fascinated naturalists since Darwin (Häckel, 1866; Thompson, 1917) and even before. But only since Darwin do we have a workable hypothesis about the driving force giving rise to the astonishing diversity of organism structures and behaviors in the world's fauna. According to Darwin, the different morphologies and behaviors are adaptations that serve the organism to survive in the particular niche in which it makes its living. For example, the evolution of a stronger and wider beak (Weiner, 1995) allows birds to crack open a type of nut that is not accessible to birds with a slender beak, and evade competition with the slender-beaked birds altogether when food sources are limited. Beyond morphology, *behavior* also contributes to fitness and is selected for depending on its adaptive value (Bateson, 1988). A good example is mate selection, a behavior that is thought to maximize the success of the selector's genes for future generations, based on the outward appearance and behavior of the selected mate.

The literature abounds of examinations of the adaptive values of morphologies and behaviors, and to a large extent the explanation of the fitness contribution of a particular morphology or behavior is all too evident to be controversial (the criticism of such an "adaptationist program" (Gould and Lewontin, 1979) has been repudiated effectively (Dennett, 1995)). Still, except for the observation of changes of

beak sizes of Darwin's finches on the Galapagos mentioned above, and relatively recent events such as the radiation of the Cichlid fishes (Barlow, 2000), the emergence of form and behavior in response to the environment cannot be examined via real-time experiment, but has to be inferred from the fossil record instead.

For simpler organisms such as viruses and bacteria, Artificial Life has made a tremendous impact on our ability to study evolution *experimentally* (see, for example, Adami (2006) for a recent overview), in particular by being able to construct environments (Chow et al., 2004), record the entire ancestral history of a lineage (Lenski et al., 2003), and measure the influence of chance and history on adaptation (Wagenaar and Adami, 2000). The possibility for Artificial Life to have a similar impact on the evolution of morphology and behavior emerged with Karl Sims' introduction of his virtual creatures (Sims, 1994b; Sims, 1994a). Unfortunately, this potential was not realized for a number of reasons, among them that the software to implement the system was quite complex, and only ran on specialized connection machines. While Sims' idea has been taken up in different guises several times since (Ventrella, 1996; Komosiński, 1999; Ray, 2000; Lipson and Pollack, 2000; Taylor and Massey, 2001; Bongard and Pfeifer, 2003; Shim and Kim, 2003)—see in particular the overview in Taylor and Massey (2001) and references in Chaumont et al. (2006)—it appears that the overhead to create such a software is so large that the project rarely survives long enough that actual questions of evolutionary biology can be addressed.

We have recently completed the design and implementation of a replica of Sims' system (Chaumont et al., 2006) that we hope to use precisely in the manner we advocate above. While using the same components (cuboid blocks and neural networks) as Sims, as well as the same encoding of information (directed graphs of nodes and connections), we decided to use off-the-shelf (open source) physics engines such as the Open Dynamics Engine ODE (<http://ode.org>), Newton Game Dynamics (<http://newtondynamics.com>) or DynaMechs (<http://dynamechs.sourceforge.net>) that can easily be switched out. Such a flexibility ensures that upgrades of

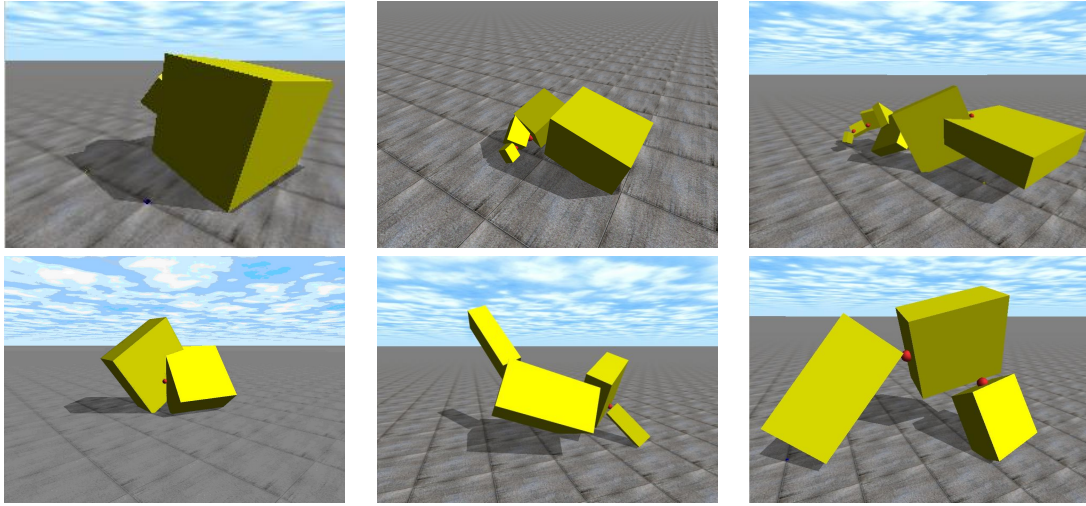


Figure 1: Sample of various evolved locomotion strategies. From top left, clockwise: Simple walker, caterpillar, crawler, quadruped, wobbler, ?

the simulator can be taken advantage of, and ports to operating systems for which one or the other simulator is not suited can be executed nonetheless.

In most of the 3D morphology implementations, organism morphology is limited by the uniformity of body parts, that is, all body parts are either blocks, spheres, or sticks, without differentiation. In our implementation, we allow for the possibility of special purpose parts—body parts that are differentiated to “arm” or “projectile”, for example, with a mutation mechanism that preserves this differentiation. We also strove to achieve a separation of physics and environment in such a manner that new experiments can be planned with a minimum amount of programming. The system is easily extendable to allow for the introduction of depletable resources, novel sensor elements, and the simulation of populations of virtual creatures.

In order to validate the basic design, we repeated Sims’ evolution of virtual walkers (Sims, 1994b) experiment and found many of the locomotion strategies he discovered, plus a few additional ones (Chaumont et al., 2006) (see Fig. 1). Only minor adjustments to the fitness landscape and to the definition of blocks and connectors had to be made to allow for the evolution of catapults, which we now describe.

Catapults

While the evolution of walkers shows how morphology and function are intimately linked, it only offers a glimpse at the opportunities opened up by experiments in behavioral and functional ecology. The selection for “forward progress on the ground” yielded a quite diverse set of strategies—among them most of those that we regularly find in animals such as two-legged and four-legged gait, caterpillar-, snake- and lizard-like motion, but also some awkward ones such as

“rolling” and “pushing” that appear to be transient forms of locomotion destined for extinction (Chaumont et al., 2006). However, this forward motion is usually achieved with relatively simple body morphology and control mechanisms that evolve periodic oscillations. We asked ourselves whether the diversity of strategies would not be larger if the selected task would require more structural complexity, and the appropriate timing of multiple neural signals by the neural controllers. We decided to select for the ability to propel a block as far as possible from the thrower’s body to test the emergence of diverse throwing strategies, that is, we decided to evolve catapults.

In order to achieve efficient selection for this trait, a few modifications of the basic body morphology had to be implemented. In particular—quite obviously so—one of the creatures’ blocks had to be detachable. This was achieved by allowing for a special type of block (the *projectile*) that sits at the extremity of another special block, the *throwing arm* (see Fig. 2). The recombination and grafting operators were modified in such a way as to preserve the integrity of the arm/projectile combination by ensuring that for each organism recombination and grafting only took place on the “remainder of the body” (defined in Fig. 2). Of course, the genes for the arm and projectile themselves can undergo evolutionary changes even if the arm/projectile topology—but not their position—with respect to the rest of the body are fixed. In particular, the shape of the projectile is optimized to allow for maximum throwing distance, as we discuss below. Also, as the arm is restricted to be a single block rather than an articulated set of blocks, standard “throwing” techniques such as those involving a bat readily emerge.

Another modification with respect to the setup for walkers concerns the neural controller. In order to coordinate the

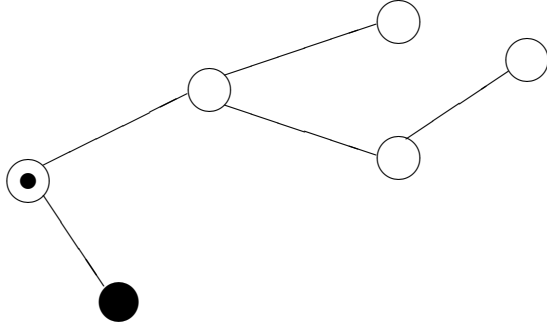


Figure 2: Schematic representation of a catapult's genotype in terms of a topological graph, where circles represent genes for constituent blocks. The arm (dotted circle) is the root of the graph to which the projectile (black circle) and the remainder of the body (white circles) are connected.

release of the block with a throwing motion, we constructed a simple architecture of four neurons that guarantees that the projectile is released at some point, while the remaining neural circuitry can intercede at any point to release the block earlier. Fig. 3 summarizes this element: a constant signal is fed through a delay neuron towards the actuator neuron that initiates the release of the projectile when it fires. A separate signal is fed through a delay directly from the neural network to the actuator. This delay is much smaller and allows for a synchronization between body movement and projectile release. Note that for the experiments described here, the delays associated with the two delay neurons were fixed, even though they can be open to evolution in principle. Similarly, the entire actuator circuitry of Fig. 3 could in principle evolve by itself. We stipulated it for these experiments simply to shorten the evolutionary time necessary to achieve the diversity of solutions observed. A more comprehensive evolutionary experiment should allow both for more freedom in the projectile/arm architecture and in the neural actuator circuitry.

Results

We selected for organisms that maximize the distance D achieved by the projectile with respect to the center of gravity of the rest of the body. The fitness evaluation can be stopped after the projectile comes to rest, which significantly shortens the evaluation period in the early generations. For later generations featuring more proficient throwers, evaluation time becomes larger because well-thrown projectiles tend to roll for a considerable distance. In Fig. 5, we show the mean fitness of the best organism (from a population of 200) from each of 17 runs. The achieved throwing distance

increases roughly linearly at first, then flattens out as the physics reaches its limits.

As we had hoped, the evolution of throwing strategies appears to be almost unlimited. Simple “pushing” techniques were prominent (while not terribly effective), but each featured a number of interesting variations. A large number of “sports-related” techniques emerged. For example, along the traditional baseball hit with a flat elongated block just after release of the projectile, a curiously effective strategy emerged that used a double-contact hit (with a broader bat) to increase projectile speed. Similarly, the “soccer strategy” of kicking the projectile involved variations including the well-known “drop-kick” idea of hitting the projectile at the moment of its impact on the ground.

Even as we began to recognize recurrent evolved behaviors, unexpected ones continued to arise. The “acrobat” seen in Fig. 4 surprised us by starting its feat while seemingly standing *on* the projectile. It then begins its motion with a violent jerk that imparts an angular momentum to the whole body so that it undergoes a summersault. At the moment the projectile reaches the highest point, it is released converting the angular momentum into forward momentum. Such a throwing strategy is commonly employed by a subset of sufficiently athletic soccer players when in-bounding the ball via a throw-in, as it generates considerably longer throws. Another unexpected strategy involved spinning the projectile with both “hands” before releasing it forward “overhead” (much like the standard soccer throw-in, see Fig. 6). The spin propelled the projectile further on the ground by adding to its forward momentum.

Other standards involved quite ordinary catapult techniques, where the weight of part of the organism was used to propel the block at the end of an opposing elongated arm. Some organisms used their arm in the manner of a discus throw but hardly moving the body, others put the weight of the entire body into it. In retrospect, strategies found in almost all sports—where sending a projectile of any shape or size over a distance is required—seemed to be re-invented by our catapults.

Beyond studying the diversity of throwing strategies, we

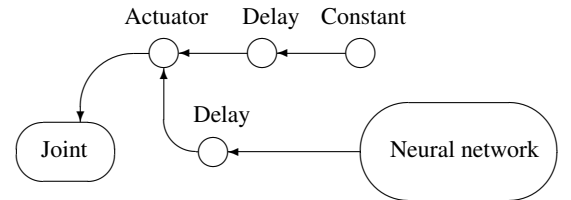


Figure 3: Schematic representation of the catapult's ignition mechanism that releases the projectile.

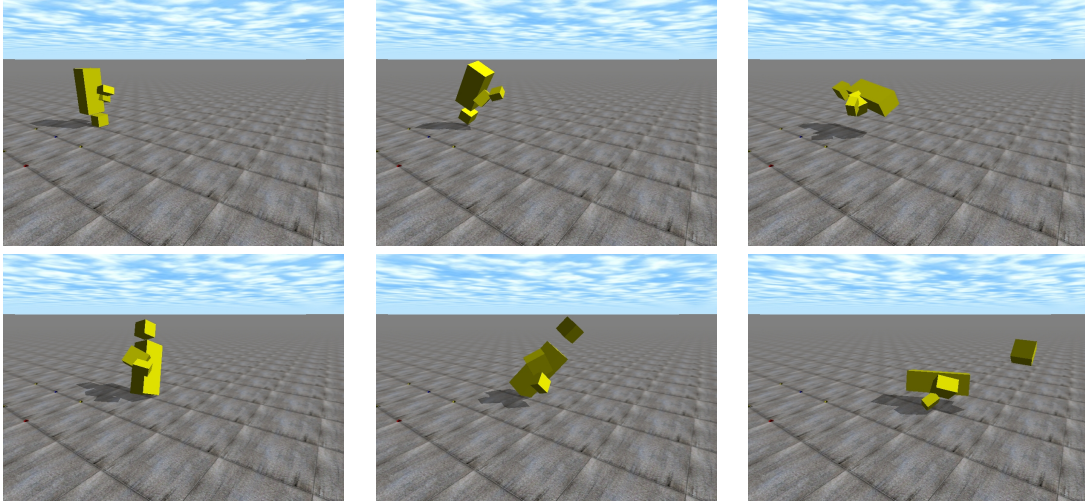


Figure 4: The “acrobat” begins standing on its “head” (actually, the projectile), then lunges forward to release the projectile just when upright on its “feet”. The forward angular momentum propels the creature to the ground while the projectile flies off.

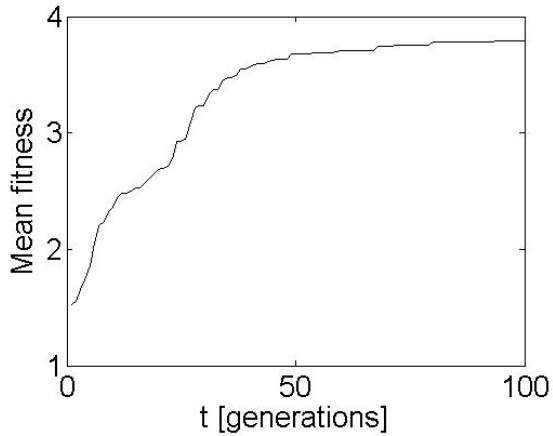


Figure 5: Average of best fitness across 17 separate runs, showing increase in throwing distance.

also looked for systematics in the optimization of single strategies. When we allowed for the evolution of the projectile itself, we observed a common trend across all strategies: the projectiles (which start out as cubic blocks) tended to become flatter and flatter while keeping a perfect square shape. We can devise a measure of flatness as a function of the three dimensions of the block a, b , and c , ordered from

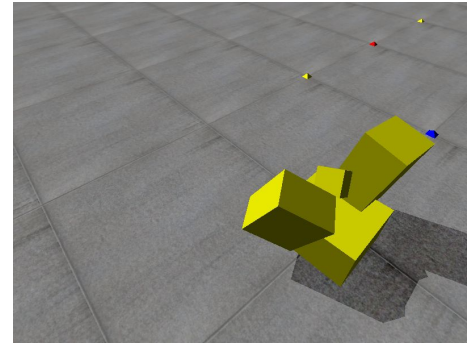


Figure 6: The “spinner”, captured at the moment just before release of the projectile. The projectile spins forward while in the air, thus increasing the distance the projectile travels as the spin momentum is converted to forward momentum upon hitting the ground. Note that the spinner uses two arms to achieve this effect, while the projectile is only attached to one of them.

largest to smallest. A good flatness measure is

$$f(a, b, c) = \frac{a}{c} - \frac{(a-b)a}{(a-c)b}, \quad (1)$$

which equals the ratio between the largest and smallest diameter if the two largest dimensions are equal (a square, flat structure), and vanishes if the two smallest dimensions are equal (a rod with a square face).

We show in Fig. 8 the evolution of flatness and fitness

(which is essentially the achieved throwing distance) as a function of time for a typical run in which moment of inertia optimization happened. Clearly, the projectile mutation to a flatter geometry significantly affects the distance traveled of the projectile.

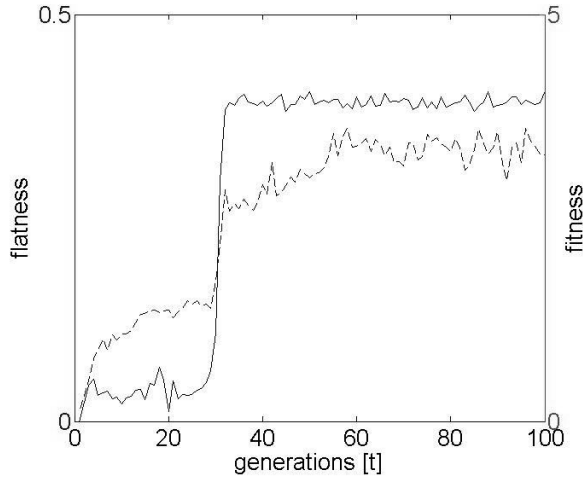


Figure 7: Flatness (as measured by Eq. (1)) as a function of time (solid line, left scale), and fitness (dashed line, right scale).

In another set of experiments, we studied whether organisms could be evolved to aim at a predefined (and stationary) point without sensory information. This indeed happens, as natural selection can provide the necessary feedback as long as the direction to aim at does not change. In Fig. 9, we show the evolution of the mean achieved angle (across a population of 100) between target (an arbitrary point about 20 body lengths away) and projectile as a function of time for a typical evolutionary run. Note that the direction of aim is hard-wired in these organisms and determined both by morphological structure and neural circuitry. Also, as the environment still rewards throwing distance at the same time (a multi-objective fitness function), the projectile comes to rest far away from the target point. In future experiments, we plan to try out sensors for light and smell. Such features coupled with local, limited resources, might allow us to gain insight into the evolution of foraging behavior, and ecological interactions.

Methods

The software is coded in C++ without parallelization and the experiments were carried out on single and dual Pentium-4 Xeon 2.6 and 2.8 Ghz workstation with 1-2Gb of RAM. The software is freely available at

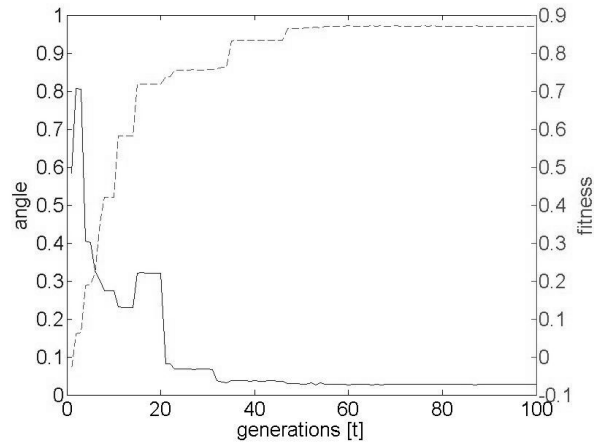


Figure 8: Angle between projectile and target (averaged over the population, solid line, left scale) and fitness (dashed line, right scale).

<http://sourceforge.net/projects/evol>. The creature's 3D environment and physics are simulated by Russel Smith's Open Dynamics Engine version 0.25 and 0.5 (ODE). Since ODE does not simulate fluid dynamics, the experiments concentrate on the evolution of ground-dwelling creatures only. To ensure a maximum of stability, each hinge joint has only one degree of freedom.

We performed several experiments varying the population size and the number of generations in such a way that the product of population size and number of generations is held constant, ensuring almost constant simulation time. While the simulation time scales roughly linearly with each of these parameters, it turns out that fastest improvements were obtained with a population of 300 individuals evolved over 100 generations. However, we noticed that the final efficiency of an individual is much more sensitive to the population size than it is to the number of generations. The same probabilities of choosing a particular operator are used in each experiment: every new creature has a 40% chance of being generated from mutations only (asexually), 30% from crossovers and 30% from grafting. The asexual operator chooses a parent among the survivor population, copies it and considers each of its parameters for mutation with a 10% probability. After a crossover or grafting, the new individual has a 10% chance of undergoing mutations, with a per-site mutation probability of 5%. More details about the particular methods can be found in (Chaumont et al., 2006).

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