Why look for Inspiration from Biology?

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In considering the use of engineered robots as elements in exploration systems, here on earth or on other celestial bodies, we are forced to emulate the existence proof provided by living systems as we know them on our own planet.

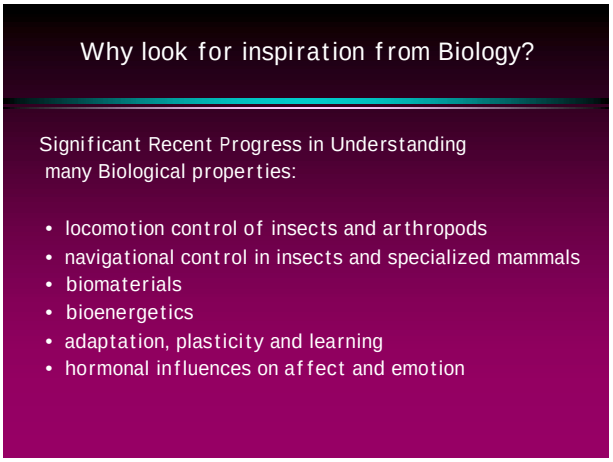
No engineered robotic system has ever been designed and built which even remotely approximates the capabilities of the lowly Cockroach or earthworm, not to mention a bird or a mouse or a human!

So what is it about biological systems that make them so special and so difficult to understand and to mimic? At what level do we need to achieve mimicry in order to capture the principles of form and function possessed by living creatures? How do we optimize the process of borrowing from nature so that we can implement the principles of her secrets in engineered systems?

These are some of the questions I have been interested in for many years. In 1984, beginning my stint as Director of Life Sciences at ONR, I stimulated the formulation of the first nationally funded interdisciplinary program designed to borrow some of nature's secrets in the area of biologically-inspired artificial neural networks. Since that time, some progress has been made in learning more about how the nervous system processes information, how neural architectures can be specialized for certain types of information processing and how a variety of general principles of neural processing might be useful for different types of artificial neural networks.

At the same time, significant progress has been made in better understanding other features of biology. Examples include:

Figure 1

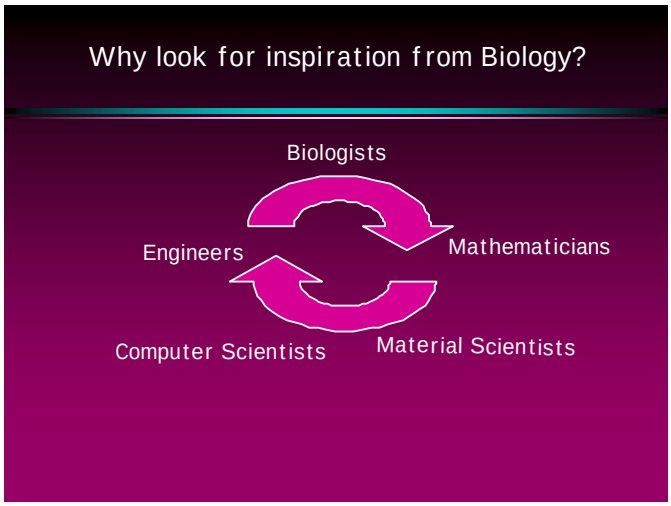


Progress in all these areas are essential if capable and robust biologically-inspired engineered systems are to be achieved. However, progress in these areas by biologists alone is not sufficient. Strong cultural, conceptual and linguistic barriers remain between most biologists and most engineers or computer scientists. Unless and until these barriers are broken down and replaced by equally strong interdisciplinary collaborations, progress in extracting and applying important principles from biology to engineered systems will remain slow.

It is clear that the engineer has much to gain from such collaborations. Biologists too, benefit from such a cross-disciplinary interaction. For example, attempts to implement in

hardware theoretical models based upon biological data can actually drive biological experimentation. It is easy for the

Figure 2



biologist to get caught in the trap of ignoring many properties of the system that the engineer must consider. Accordingly, factors such as stability and posture may not seem important to a neural model of a locomotion controller until the engineer tries to implement them in a moving robot. When faced with the problem that the biologically-inspired machine falls over, one recourse for the engineer is to ask the biologist to determine how the animal solves its stability problems. In this way, roboticists and neurobiologists can stimulate each other. Ultimately, this results in a more complete understanding of both the biological and the engineered systems.

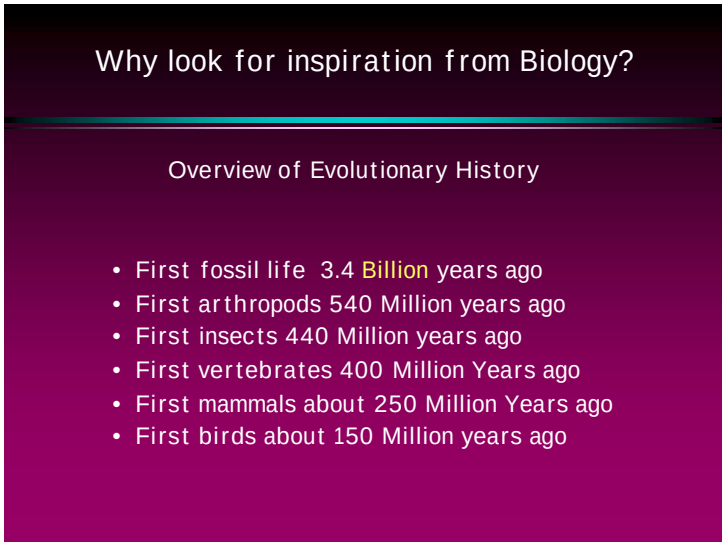
The audience in this room is, hopefully, more sensitive to, and appreciative of, the issue of interdisciplinary teaming. You represent a special community of scientists and engineers who

should understand fully both the advantages and difficulties of forging a new discipline of scientific inquiry.

In recognition of your sensitivity to, and awareness of, these issues I am a bit reticent to share some of my perspective dealing with the theme of this talk, "Why look for Inspiration from Biology?" So, let me apologize in advance if what I say is obvious or seems like preaching to the choir.

I'd like to begin at the beginning – the very history of life itself.

Figure 3

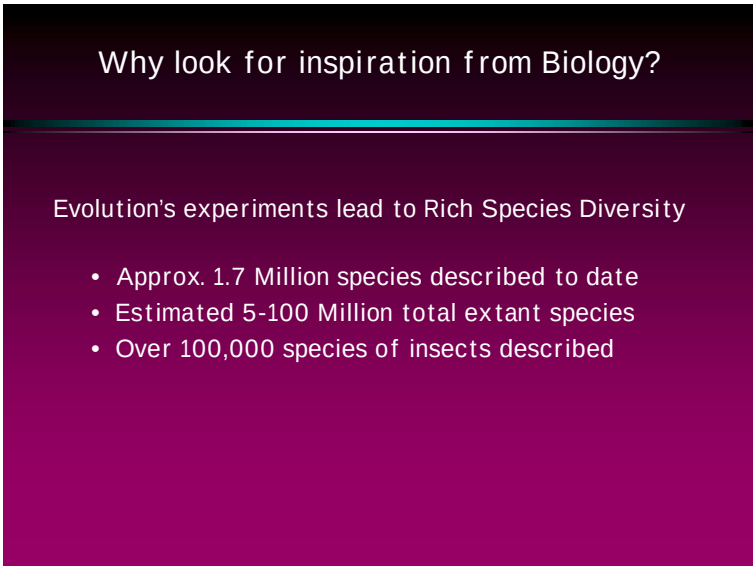


Species Diversity

All this evolutionary background is simply a prelude to make two fundamental points:

- First, nature has had vast opportunity to learn from her mistakes and to perfect and conserve those features of biological systems that confer survival advantage to species. Mankind has been seeking to understand some of the more interesting features of biological systems for less than a few hundred years at most and quantitatively for less than 50 years!
- Second, the history of life on earth and the evolution of species have resulted in vast diversity of form and function. To date, approximately 1.7 million species have been described at the global level. Current estimates of the total number of species in existence vary from 5 million to 100 million! There are over 100,000 species of insects already described and perhaps 20X that number still to be discovered!

Figure 4



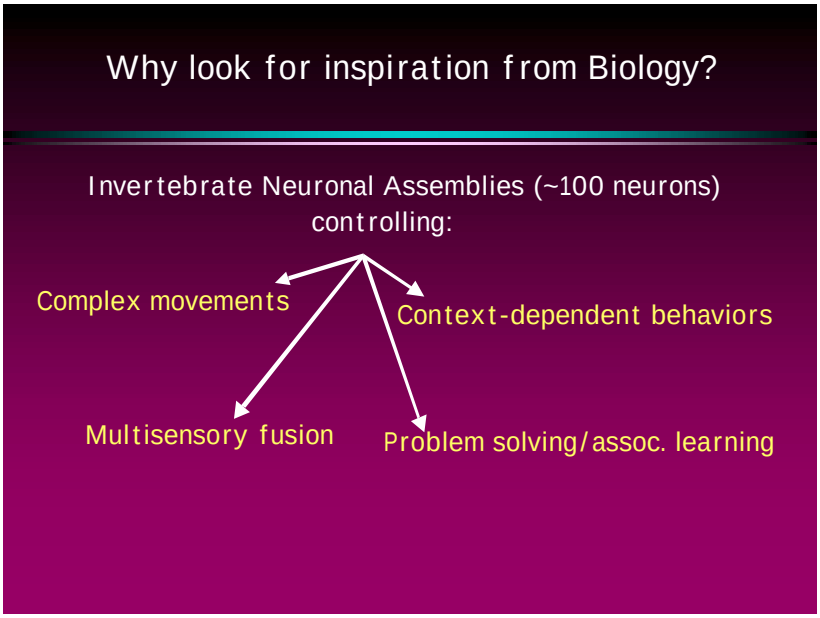
This extraordinary diversity coupled with millions of years of trial and error to get it right provide an almost unimaginably rich data base from which to seek inspiration for biologically inspired engineered systems. In fact, the database is so rich that it is easy to get lost in it. Specific model systems have emerged as principle targets of investigation. The cockroach, the honey bee, the lobster, the dolphin, the bat, the butterfly, the moth, the rat, the earthworm, the locust and yes, even the human have all provided important insights into some of nature's secrets.

I want to focus the remainder of this talk on a number of interesting features and characteristics of neural systems that provide important sign posts along the road of achieving capable biologically-inspired robotic systems.

The biological systems I want to focus on are mostly found in invertebrate phyla. There are many advantages of studying such "simple" systems for the purpose of borrowing from nature's 400 million years of experience to apply to engineered robotic systems. First, the number of neurons involved in invertebrate systems is orders of magnitude smaller than in nearly all vertebrate systems. Individual neurons can be unambiguously identified and filled with markers while their individual as well as system level properties are studied. The mechanical properties of leg joints in invertebrates are generally less complex than vertebrate joints. The cost of doing experiments with invertebrates is much lower than comparable research on vertebrate systems.

While being more technically approachable, invertebrate systems are far from “simple”. We find populations of as few as 100 or more neurons controlling complex movements, context dependent behaviors, interactions between pattern generators and peripheral sensory structures and sophisticated sensory processing. Insects are even fully capable of solving problems involving associative learning. All this with relatively few, on a biological scale, neural processing elements.

Figure 5



What are some of the properties of invertebrate systems that can provide engineers with inspiration for robotic application?

<u>Graceful degradation:</u>

Engineered robotic explorers will not be repairable in the field! Failure needs to be minimized. Invertebrate (and vertebrate) control systems have the remarkable property of being able to adapt if a body part is damaged. Automatic control system adaptation allows the remaining parts to continue to function reasonable normally. This kind of design feature would be especially useful in planetary explorers where the cost of a duplicate control mechanism might be prohibitive. Robotic systems that could function in spite of damage would have enormous benefits.

Orienting and Escape Behavior:

A fundamental emergent property of nervous systems is the ability to orient to novel stimuli in the environment. This property has obvious survival value for both predator and prey alike. It clearly would be a capability of certain types of robotic explorers that could be very useful. In the case of the cockroach, for example, the detection of even slight air pressure changes on the mechanoreceptor hairs of the cerci, two antenna-like appendages on the rear of the animal's abdomen, leads to orientation and escape. Air puffs with speeds as low as 12mm/sec. Evoke an escape response that is directionally opposite from the direction of the detected wind. Interestingly, the cockroach is able to discriminate between ambient air movement and air movement fronts caused by potentially threatening predators. Accordingly, the escape response is only triggered when air movement accelerates at 0.6m/sec.squared or greater. Neuroethologists have studied this system for many years and the elegant nature of the sensory-motor system underlying this fundamental survival system has been well documented. What appears, at first to be a simple escape reflex is actually considerably more complex. The cockroach does not simply jump

and run in response to a threatening wind puff. Rather it senses the direction from which the treat came and then orients its escape path away from that source. The principal cues for this decision are the directional properties of the wind puff. However, the cockroach interprets the wind information in the context of a wealth of additional information, including sensory cues monitoring its immediate surroundings, the position of its limbs, and its current physiological state. It accomplishes all this sensory motor processing in about 20 ms. In short the cockroach possesses all the requirements for a successful crash or obstacle avoidance device.

An understanding of how the cockroach performs these calculations and executes a successful escape behavior in a remarkable short time may shed light on how similar control circuits could be constructed and implemented in a robot. By studying a variety of invertebrate systems and their neural control circuits, nature's solutions might inspire new engineering principles. For example, rate-dependent sensors could detect a dangerous situation in the same way as acceleration-sensitive hairs on the cerci differentiate between wind puffs originating from lunging predators and those coming from non-threatening sources.

Biosensors for Chemical Detection:

Robotic explorers having the capability to detect and locate specific chemical signals at some distance from their source would be very useful. Here again, biological models may be useful in inspiring the design of control systems as well as actual sensor elements to carry out such functions. Many life forms have the ability to orient their movements towards goals and away from threats. Natural

orientation systems have benefited from millions of years of evolution.

Successful locomotion to a target requires that an organism or a robot (1) produce appropriate forces to overcome gravity and propel the body, (2) stabilize the orientation of the body during locomotion, e.g., through bilateral and longitudinal coordination of appendages, and (3) orient the resulting movements in a direction appropriate to navigate to the goal. This last task becomes considerably more difficult in an unpredictable environment, or when a discrete representation of he target's location in space is not available. Sensory cues of several modalities may have to be fused to control the orientation of locomotion, and the control system must be adapted to overcome the indeterminate nature of a changing environment.

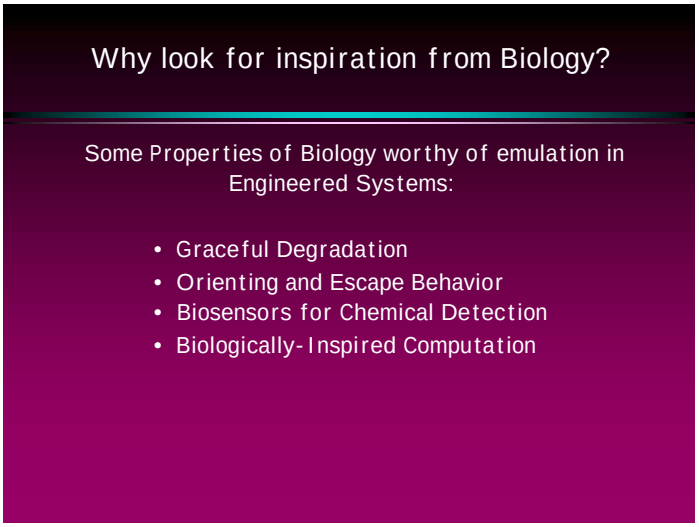
Many animals find unseen targets such as mates, home sites, or food by tracking odors. These chemical cues may form gradients or trails or, when borne in air or water currents, may form turbulent plumes. Locomotion guided by chemical gradients or trails may involve simple behavior like turning toward one side or the other providing higher-intensity signals to individual or paired sensors. Orientation in a turbulent plume is more complex for detecting chemical agents that are suspended in the moving current and requires multi-modal control systems and responses both to chemical signals and to the air or water current.

Several species of fish and birds and a large number of flying insect species locomote toward, and successfully locate, distant unseen sources of odor. In many cases, and across many species, the paths traveled through air or water on the way to odor sources are very similar to each other and appear as a complex zigzag pattern. Although present in many animals, this type of chemically modulated orientation behavior finds its greatest expression among the insects. Males of many species of moths, for example, are attracted to receptive females for mating by complex blends of airborne sexual pheromones.

There is now considerable understanding of the sensory and underlying neural substrates responsible for mediating chemical gradient orienting behavior. Suffice it to say here that multimodal sensory information about the animal's movement, combined with odor quantity, quality, and the temporal structure of the plume, is integrated with patterned, self-generated motor outflow to result in coordinated upwind locomotion to the target. If engineers could borrow from nature the secrets underlying the algorithms employed by insects for odor-source searching, that knowledge would be useful and efficient in leading to novel engineering designs for subsystem controls in autonomous or semi-autonomous robots.

The rapidly developing field of silicon-based molecular sensors coupled with a better understanding of the principles of chemical gradient detection evolved over hundreds of millions of years of evolution should lead to biologically-inspired control architectures for engineered systems capable of sophisticated chemical detection in uncertain and unpredictable environments.

Figure 6



Biologically-Inspired Computation:

Nature's most interesting secret, yet to be discovered by man, is perhaps the secret of emergent properties. Animals with even rather simple nervous systems are capable of rich and complex behaviors. They achieve these behaviors by relying on considerable computational power derived from multiple independent, simple and small task-achieving computational modules, executed in parallel in a fully distributed manner.

When a lion is chasing its prey, it is not repeatedly measuring the distance every, say 50 ms (i.e., each 83 cm of progress at 60 km/h) to the nearest obstacle (e.g., a tree) to avoid it. Nor is it simultaneously calculating the angular momentum generated, for example, by the rotating forward half of its body to adjust the trajectory of the body's gravitational center to that of the escaping prey. Computation of the exact volume of its body needing to be tilted would also be a major problem, not to mention the angular adjustments of bones at each joint, and the energy needed to reform the bone structure that supports the tissue mass. All these computations are done seamlessly and without central control.

This example is meant to motivate our thinking about how an autonomous robot might someday be conceived. Most likely such robots will not have explicit plans. They will probably have a list of jobs to be achieved in a loose time limit, but generation of precise task sequences will be emergent and management of the scheduling probably left largely to themselves. The actual order of task execution will be determined dynamically as a result of self-organization.

How would such an autonomous robot be “controlled”? More than likely we would want to design a system with center-less control. Interestingly, in many respects, the concepts of autonomy and control are mutually exclusive. The term “autonomous control”, routinely used, is somewhat of an oxymoron. Hierarchy of control might still appear in autonomous robots but it would most likely be an emergent property, as it is in biological systems. The realities of robotic exploration will require robots to work in an increasingly more dynamic, flexible, and robust manner in order to deal with the non-linearities of the real world. Achieving such capabilities will require radically different thinking towards the engineering solutions required. A fundamental understanding of emergent properties as seen routinely in biological systems may be a necessary prerequisite to borrowing the underlying biological principles and applying them to engineered systems.

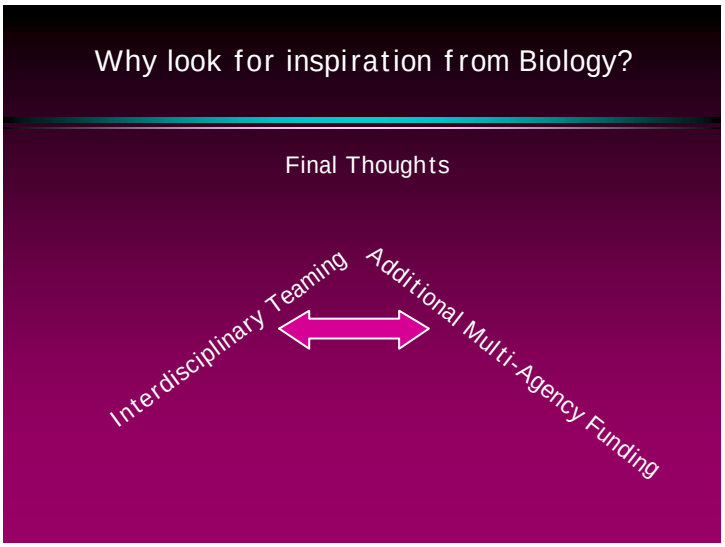
Some Final Thoughts:

Historically, traditional engineering approaches to robotics and robotic control have not embraced biological inspiration. This is neither surprising nor even wrong. Much like nature, learning from her mistakes and successes, we too learn from ours. Traditional approaches to robotics have failed to produce robust and capable autonomous designs. There is much to be learned from these failures.

We now have a window of perhaps 20 years during which time we are challenged with the opportunity to develop a new generation of biologically-inspired robotic explorers with capabilities beyond anything previous robotic designers ever achieved. In order for this to happen, however, a few critical elements must converge. First, there must be much more interdisciplinary teaming

between biologists, engineers, computer scientists and material scientists. These teams are essential to both formulate the right questions to be asked of biological systems and to be able to apply the principles extracted from biology back to engineered systems. Second, there must be more funding from NASA and other agencies to support and nourish such a major scientific and engineering endeavor.

Figure 7



Historically, mission planners have been limited by their knowledge of the available technology. We must engage current mission planners and stimulate their imagination with the possibilities for new mission concepts and opportunities based upon new capabilities of future robotic explorers. Of course we must begin to demonstrate the reality of these new capabilities, even if they represent only small incremental steps towards a much more capable end point. This is not an easy sell. Nor is it an

easy set of R&D issues to solve. Many will fail. Some will succeed.

It is my view that the challenge we face in creating biologically-inspired engineered explorers is one of the most interesting and fundamentally important challenges science and technology have ever faced.