Dr. Steven G. Wax
Defense Sciences Office (DSO)
Enhancing System Performance: Exploiting Nature through Materials and Design

Good Morning. Michael has done a wonderful job describing our vision of how the revolution in biology will make a huge difference in tomorrow's defense systems. Following my presentation, Joe Bielitzki will describe how biological sciences can affect changes in the capabilities in human performance of the warfighter and perhaps he will have some hints for how I can get to look like the picture Michael showed.

But first, I want to discuss something less obvious—but equally powerful—how understanding nature and effecting that understanding through the development of new materials will enhance the performance of systems that support the warfighter.

So what is so special about biology aside from the fact that without it none of us would be here today?

The octopus, shown courtesy of Roger Hanlon at Woods Hole Marine Biological Laboratory, displays a very dramatic example of camouflage.

(Octopus Movie Shown)

In addition to having incredible self-protection mechanisms such as the one shown here, biological systems are also self-propelling, self-fueling, self-healing, completely adaptive in very dynamic environments, and even self-replicating, essentially completely autonomous. These characteristics, with the possible exception of self-replication, mirror exactly the characteristics one would hope to achieve in defense systems.

In addition, nature has provided a great deal of fault tolerance in its species again essential in the new way defense does its business. As Michael said, we must imagine. And so, imagine if we could leverage our understanding of biology to impart these characteristics on the varied systems and devices that make up our defense arsenal.

From the planes we fly to the uniforms our soldiers wear. Looking closer at the octopus, we see that it accomplishes this camouflage trick by a very elegant process: the octopus skin is virtually transparent, containing layers of color-producing cells known as chromatophores.

The size of each chromatophore is manipulated by a set of muscles controlled by individual nerve endings. By varying the cell size, the octopus can vary the color, hue saturation, and brightness of the chromatophore. By varying several cells simultaneously, it can control general skin coloration and overall body pattern.

Having a nerve ending controlling each cell allows for rapid and precise control (on the order of milliseconds) of the skin's camouflage process. Additional muscles in the skin control the body texture of the octopus.

Cephalopods are not the only animals capable of this type of camouflage. A flounder, for example, can even adapt to a checkered background.

But, while it is true that we would love to be able to reproduce the camouflage behavior of the octopus, it isn't clear that the way it is done in the octopus is the best way or even a feasible way to do it in man-made systems. Clearly it is good to be inspired by the observations of unique structures or functions in nature. But it is not always true that copying nature exactly in terms of design features, materials, and process in other words, being biomimetic is the best approach to take.

Sometimes we can steal the inspiration from nature, often called "bioinspiration," and then use more traditional engineering approaches to make it happen.

The airplane is a great example of bio-inspiration, but it is certainly not biomimetic. Often, the best approach is a combination of both of these attributes.

So, the point of this talk is not to impress you with the wonders of nature that is just the starting point. The purpose is to show that understanding nature is necessary but not sufficient to accomplish our goal of enhancing system performance.

As Phillip Ball said in January 2001 issue of Nature: "Nature's pool of ideas is only valuable if it can be translated into terms that the technologist can work with, particularly in terms of materials and processing methods."

Or to put it in a common vernacular understood by material scientists everywhere: it's the materials, stupid! And it is the material science challenges of the biological revolution that I want to stress in the remainder of my talk.

For while we have made some impressive progress, I hope to show you that there are many fascinating "DARPA-hard challenges in materials and materials design that remain to be overcome before we can capture the capabilities of the biological world for the benefit of defense.

In a general sense, it is easy to understand why this is such a difficult problem. Nature deals with small, curved materials and structures, full of bends and twists. Man made objects, on the other hand, tend to be large, flat, angular and stiff. I think the best way to illustrate the great potential and, more importantly, the challenges of this facet of harvesting the biological revolution is through examples of research underway in our office.

And, the most logical place to begin is with something that nature does very, very well—locomotion. I will let the Army argue with itself about whether wheels or tracks are better. Regardless, our research has shown that if one wants the dynamic adaptability and the locomotion capability across complex surfaces as we see in animals, legs are the thing!

But it isn't just having legs that leads to that capability. Many have tried to build legged robots with limited success. Rather, it is understanding the way they are used and how they are constructed that is critical. When animals walk or run, they don't do complex calculations about where to place a leg or how to balance the body.

Neither do we. Though the brain might tell you where to go, the act of locomotion is controlled locally by the physics of the legs themselves.

(Cockroach Movie Shown)

Take the cockroach. It is able to move over complicated, fractal surfaces very rapidly in a fault-tolerant manner. This is because the cockroach locomotes based on the principle of a pendulum in which the weight of the cockroach shifts automatically to balance the movement. This is done locally without "thinking" in the classical sense.

To demonstrate this approach, we built a shoebox-sized robot that walks based on the same principle. This robot has been tested by the U.S. Marine Corps at Southwest Research Institute with very dramatic results. It has been shown to be able to maneuver over unplanned terrain going where wheels can't.

For its size, it performs better than any wheeled or legged robot tested. It can also swim, I might add!.

(Video)

Though impressive, this is really a relatively simple example of mimicking biology's locomotion capabilities.

To fully emulate locomotion, one would need to fully imitate the behavior of the muscles. Long before you realize you have switched from dirt to sand, your legs have reacted and adapted. This is because a significant part of the feedback system for biological locomotion actually occurs in the muscles themselves.

Not only do muscles act as actuators, but they also serve as sensors providing local position. And they have a structural role as well, supporting weight and acting like a spring and damper. Muscles are, in fact, many machines rolled into one. And, they do this while still being very soft and very compliant, as one would expect from nature.

Looking at the muscle, it is clear that this is a hierarchical structure of fibers within fibers allowing each small movement of tens of nanometers to be translated into very large motions. This leads us to one of the greatest challenges in the development of materials and material concepts: the way nature builds its structures is simply spectacular.

Nanotechnology may be a current buzz word in the materials research community, but through eons of evolution, biology has been at work developing structures that begin at the nanoscale and then continue in a very precise architecture to the macro-scale.

While there is much research on areas such as self-assembly, we have not yet learned how to apply this to building complicated structures the way nature does. That is not to say we haven't had some success at emulating muscles.

For example, we have begun to make fibers within fiber constructions that will actuate in the same fashion as muscles. The similarity is striking, although this is just in the beginning stages.

Further along, though more bioinspirational than biomimetic, is a simple elastomer that will electrostatically expand and contract when an electric field is put across it.

(Run Movie)

With clever electrode design, the material can be rolled up and then made to expand and contract with multiple degrees of freedom.

(Run Multi dof)

It also has sensing capability built in allowing the artificial muscle to have some awareness of its position. According to simulations, this should provide the kind of behavior that will allow natural-like locomotion.

(Run Simulation)

But this rolled up plastic, while on the right track, is a far cry from the structural wonder of a natural muscle. Ultimately, if we really figured out how to make soft, compliant muscles and structures, then once again the octopus would show what might be possible!

(Second Octopus Movie)

Emulating muscle isn't the only opportunity in biomimetic locomotion. Take our investment in understanding the Gecko's ability to climb walls for example.

(Movie of Gecko)

If one examines closely what allows this creature to defy gravity, the secret is in the millions and millions of cilia that make up its foot pad. It appears to be Van der Waals forces that are in play. In addition, the foot is self-cleaning. Wouldn't it be great if we could develop a material that soldiers or robots could use to climb walls?

There are some thoughts about how one might emulate this behavior, however, exactly how one might build such a structure out of engineering materials remains a challenge. Maybe it's a role, finally, for carbon nanotubes.

And the final frontier of locomotion flight is something quite prevalent in nature. We have, of course, been able to emulate that mode quite well from large transport aircraft to 6-inch micro air vehicles. However, for very small structures operating at very low Reynolds numbers, it seems that copying the mechanisms of the flight of insects offers great promise.

(Insect Flight Chart)

Definitive studies on how this works have shown that the wings create a vortex and then actually use this vortex on the next wing stroke to increase lift.

Recently, we have been able to create an artificial insect a two centimeter, flapping wing modeled from the blowfly that flies using the same principle. This model uses a simple PZT-actuated thorax for wing actuation, and so far it has only flown tethered and using one wing. But this is still an impressive demonstration using existing materials. Perhaps with the introduction of artificial muscles and more biologically-inspired materials for the wings, the performance could even be more dramatic.

Before leaving locomotion, it is interesting to note that even for large-scale flight—something we seem to have done quite well over the last 100 years—nature offers some improvements.

We currently design our aircraft as fixed structures, making small changes in the aerodynamics using flaps and rudders. But when birds fly, they make global changes in shape. And so we are embarking on a program to see if we can do the same kind of morphing in aircraft structures. If successful, this would allow aircraft to have one configuration at low-speed, long-endurance flight and then reconfigure for high-speed attack exactly as birds do now.

While locomotion is obviously critical to defense systems, another area that biology excels at and that is essential to defense is sensing. Let's begin with one of my favorite examples, the Melanophila (MELANO FILIA) beetle.

Reproduction is one of the driving forces of nature, and this beetle's reproductive strategy is to lay its eggs in burned-out wood (a great example of hot sex no doubt). Because reproduction is key to survival, this beetle has developed the ability to detect forest fires from 60 miles away.

Put in defense terms, it has the capability at 0.3 microns wavelength to measure radiative power that translates to 0.003 oC resolution, thus making it an incredible room temperature IR sensor.

The organ the beetle uses to accomplish this has been characterized. It is believed that the mechanism is the expansion of the sphere due to absorption of IR radiation that causes a 1nm deformation of the dendritic tip and provides a signal to the beetle.

However, once again, the difficulty is to actually build this out of man-made materials. Some work at the U.S. Air Force Research Lab is trying to reproduce this, but we again are still far from recreating this capability and having a room temperature IR sensor based on this principle.

The way nature exploits the visible part of the electromagnetic spectrum is equally impressive. For example, we are attempting to emulate the lens system found in a fish eye, which is capable of dynamically controlling its field of view. This is accomplished by having a lens that can switch from wide to narrow field of view by structurally changing the index of refraction almost instantaneously.

Currently, we use heavy, complicated, and expensive lens systems to achieve wide field of view optics in defense systems. What if we could create the rapid index of refraction changes in materials and produce man-made lenses that respond as the fish eye does? This would allow us to reduce the size, weight, and cost of current optical systems and at the same time significantly improve performance.

In a new program, this is exactly what we are trying to do. But the challenge is daunting, requiring a dynamic index change of over 1.0. So, stay tuned.

We have also emulated some of the pre-processing that takes place within the retina using conducting polymers. This approach will allow analog image processing at 10 times faster and using 10 times less power than digital approaches.

As these examples have shown, the way biology builds structures is exceptionally efficient. This is in sharp contrast to man-made structures. When we build a defense system, every component has a single function, each is designed in isolation, and the system is the sum of these components. Nature's structures, on the other hand, evolved in unison and use multi-functionality to provide extremely efficient and practical designs.

For example, the cuticle of a beetle is a marvelous material. It has chitin fiber nanometers in size with very specific orientations and volume fraction all designed for structural support. It is surrounded by a protein matrix that controls water content, modulus, and pH. It also has pore canals connecting the epidermal cells to the cuticle, allowing communication and repair but without the porosity weakening the structure. Thus, this one material serves as structure, thermal management control, armor for protection, and a host of other functions.

It is not clear we could even begin to design such a system, let alone actually construct it. It is but one example of how nature puts multi-functionality into its systems. We have had some very impressive successes in the area of multifunctional materials structures that contain porous materials for thermal management or structures that are integral with fuel cells or batteries. But we are nowhere near approaching the full breadth of what nature can provide.

In conclusion, I hope it is clear that much work is being done and will be continue to be done on understanding how nature works. However, we have only begun to scratch the surface on how to realize these wonders in real materials and structures. Artificial muscles, complicated vision systems, morphing structures, multifunctional materials all are on the table as very hard research problems. Imagine if we could translate all of these into the defense of the future. It's a formidable adventure that we have just begun to set out on.

We would love to hear your ideas on unique and powerful ways to get there.

I should mention that I owe the examples I used to quite a few program managers, including Alan Rudolph, Leo Christodoulou, Len Buckley, Ephrahim Garcia, and Dennis Healy, each with diverse backgrounds in zoology, materials, chemistry, aerospace engineering, and mathematics, respectively.

In many ways the diversity of the program managers involved pays homage to the interdisciplinary nature of the problem, making it a perfect challenge for DARPA, in general, and the Defense Sciences Office, in particular.

And now, Joe Bielitzki will tell you how we plan to exploit the biological revolution to convert hapless DARPA PM's into well, I'll let Joe explain it.