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DSO Approach to Materials Science

Good morning. We've heard how DSO is pursuing new strategies in complex systems and biology to enhance situational awareness as well as human and system performance. I would like to continue the DSO dialogue by talking about some of the exciting research activities we are pursuing in the material sciences. The exploitation of new technologies ultimately drives a need for new devices and structures that exhibit superior functionality and performance. These new devices and structures, in turn, will require new materials. For this reason, materials research has been, and will continue to be, a fundamental strength of the DSO investment strategy. I hope that in the next few minutes, I will be able to give you an appreciation for the sort of revolutionary changes and new capabilities that DSO is pursuing through our material research and development efforts.

DSO's investments in materials research are, of course, carefully chosen with an eye toward the future, revolutionary capabilities that might be made available to the Military Services. Developing materials with unprecedented properties that can deliver these future capabilities sometimes means inventing entirely new classes of materials. Stu Wolf's Spins in Semiconductors Program, where quantum mechanical spins will transport information in ways never before dreamed possible, and Leo Christodoulou's Structural Amorphous Metals Program, where metals with unprecedented strength, and wear and corrosion resistance are being developed, are two examples of DSO programs that are funding research aimed at demonstrating entirely new types of materials. On the other hand, sometimes achieving superior material properties means finding new ways to put "old" materials together. For example, DSO is funding a number of basic research activities aimed at developing and demonstrating thermoelectric and magnetic materials with properties that significantly surpass the state of the art. I would like to tell you more about some of these activities that are being funded through DSO programs including the Advanced Thermoelectric Materials and Devices Program, the MetaMaterials Program, and the BioMagnetICs Program.

First, let's talk about thermoelectrics. A thermoelectric material can be used in one of two ways. If you pass an electric current through a thermoelectric material, it will develop a temperature gradient in the direction of the applied current. Therefore, thermoelectric materials can be used for refrigeration and thermal management applications. On the other hand, if you impose a temperature gradient across a length of thermoelectric material, it will develop an electric potential along the direction of the temperature gradient. This means that thermoelectric materials can also be used for generating electric power from thermal sources. Unfortunately, since their first demonstration in the 1960s, the limited performance of thermoelectric materials has traditionally precluded the use of thermoelectric devices in all but a few niche markets such as temperature control for optical devices or power generation for deep space missions like Voyager I and II. By the mid-1990s, despite decades of extensive research investments, no significant improvements in the performance of thermoelectric materials had been achieved.

To understand why improvements to thermoelectric materials are difficult, one must understand that a "good" thermoelectric must exhibit a combination of properties that simply do not coexist in conventional materials. A desirable thermoelectric exhibits the high thermopower found in semiconductors, the high electrical conductivity observed in metals, and the low thermal conductivity observed in insulators. The combination of these properties is captured by the thermoelectric figure of merit ZT. In 1995, DSO initiated the Advanced Thermoelectric Materials and Devices Program. The goal of this program was to advance the figure of merit from a value of 1, a record held for nearly 40 years, to a value of 3 to 4. Many researchers would have regarded such a goal as "fantasy."

Now let me show you the new state-of-the-art in thermoelectrics. This breakthrough was achieved when DARPA researchers developed a new way of putting together thermoelectric materials. Scientists at the Research Triangle Institute demonstrated thin film superlattice thermoelectrics that exhibit a factor of 2-3 improvement in performance over conventional materials. These superlattices promise unprecedented, solid state, cooling, heating, and power generation capabilities for a number of DoD and commercial applications such as temperature control for DNA microarrays, on chip cooling for microelectronics, and electric power generation for future electric vehicles. The realization of these new capabilities will complete the transformation of a DSO impossible vision to a new reality for thermoelectrics.

RTI's superlattice structures provide an excellent example of how an engineered nanostructure can significantly improve performance in one particular class of materials. How you put a material together is just as important as what you put together. This result provided part of the motivation for another DSO initiative, the MetaMaterials program. Perhaps you are asking yourselves, "What is a metamaterial?" A metamaterial is an engineered composite that exhibits superior properties not observed in nature or in the constituent materials. The superior properties of a metamaterial are a result of their engineered constructs. The MetaMaterials Program asks material scientists to think like material engineers in order to develop materials that will fill voids in the design spaces of many important DoD applications. This is the program that will give design engineers a license to dream, to think out of the box—free from the constraints imposed by the performance limitations of conventional materials. We are exploring a number of engineered composites in the MetaMaterials Program. One class of materials being developed is high-performance magnets.

You may not appreciate the pervasive role that magnets play in your everyday life. Magnets are used in the motors that run computer hard drives, VCRs, ceiling fans, windshield wipers, and many other items. If you begin to count the everyday appliances that use magnets for motion alone, you would quickly find this number approaching the hundreds, perhaps thousands. The world market for magnetic materials today is approaching $20 billion and is anticipated to continue to grow at a rate of about 15% per year. However, traditional magnetic materials lend themselves to applications that are relatively low in power density, a direct consequence of the limited performance of available magnetic material.

Imagine electric motors powerful enough to propel our naval ships through the seas, our aircraft through the skies, and our tanks on the ground. In the same way that hybrid cars with electric drives are beginning to permeate our roadways, all the Military Services have visions for a transformation to more electrically driven platforms. The Navy has the Electric Warship Program, the Air Force has the More Electric Aircraft Initiative, and the Army has Future Combat Systems. Electrically driven platforms offer a number of major advantages, including reduced logistics, quieter operation, and improved fault tolerance. High-performance magnets are an enabling technology for achieving these goals. One of the objectives of the MetaMaterials Program is to develop engineered, nanocomposite permanent magnets with superior properties for high-power density applications such as electric drive and propulsion. Nanocomposite permanent magnets are an excellent example of a metamaterial. I like to think of them as the "canonical" metamaterial because, as I will show you, it is easy to see graphically how the engineered nature of these composites results in their superior properties.

The performance figure of merit for a permanent magnet is the energy product. The energy product is obtained from the product of two intrinsic magnetic properties: saturation magnetization and coercivity. Unfortunately, nature gives only one or the other: soft magnets have high saturation magnetization and low coercivity, while hard magnets have high coercivity and low saturation magnetization. What you would like in a permanent magnet is the high saturation magnetization of a soft magnet and the high coercivity of a hard magnet. However, using conventional approaches, a hard/soft magnetic composite does not provide any improvement to the figure of merit. You get a material that behaves a little bit like a hard magnet and a little bit like a soft magnet. Now consider what can be done using a metamaterial approach. If the structure of the hard/soft magnetic composite is engineered so the moment of the soft magnetic material is held fixed by the magnetic field of the hard magnetic material, it is possible to achieve significant enhancements in the energy product. Achieving this result will require precise control of the nanostructure of the hard/soft magnetic composite. Researchers in the DARPA MetaMaterials Program are working to demonstrate engineered hard/soft magnetic nanocomposites with enhanced energy products. If they are successful, it is believed that magnets 50 to 100 percent more powerful than today's magnetic materials will be available. The demonstration of these materials is a major step toward demonstrating electric drive and propulsion for our future military platforms.

Magnets can be used in biology, as well. In this case, the magnets might be extremely small. I believe that nanoscale magnetics offers a particularly attractive approach toward interfacing microelectronic devices with biology. DC magnetic fields have little or no effect on living organisms and can be applied without having to make direct contact. In DSO, we initiated a new exploratory program that is investigating nanoscale magnetics as a way to interface with biology. The BioMagnetic Interfacing Concepts Program will bring new meaning to "cellular" communications. In this program, we are developing nanoscale magnetic materials that can be used to impart a well-defined magnetic moment to single cells and biomolecules. If one can make cells and biomolecules magnetic, one can use magnetic sensors and fields to detect and manipulate them. Depending on how and where magnetic moments are attached, magnetics might be used to control biological function. This would be a tremendous capability since living cells exhibit a wide range of powerful functionality. They can grow, reproduce, express proteins, perform complex information processing operations, and even change color—all in response to chemical signals that are present in their environment. Imagine if we could exploit this functionality in therapeutic, diagnostic, and sensing devices that can be taken out of a laboratory environment and placed in the hands of our military personnel. Such devices would require the ability to seamlessly convert biochemical signals to microelectronics. Biomagnetics offers a portable, robust transduction mechanism for interfacing the chemistry of biology and the electronics of functional devices. In the BioMagnetICs Program, we are beginning to develop the tools that will allow nanoscale magnetics to be integrated with biology and demonstrated as a powerful new transduction mechanism for the detection, manipulation, and functional control of cells and biomolecules.

One example of how magnetics can be applied to biology is the work being done by researchers at the John's Hopkins University to attach magnetic nanowires to cells. Because of their large aspect ratio, these wires have an artificially high magnetic moment that makes them easily maneuverable in the presence of small, external magnetic fields. See here how wires attached to this single cell can be used to manipulate and rotate the position of the cell. Now consider multiple clusters of cells, each made magnetic by attaching a magnetic nanowire. See how they can be made to move and rotate in a collective manner—much like a cellular ballet orchestrated by unseen magnetic musicians. Imagine how one might be able to use this capability to arrange these cells in specific patterns. It is easy to envision how these tools might be used in a wide range of biotechnology applications-from tissue engineering to cell based sensors to high throughput DNA screening. As a last example of how DSO material investments can lead to new capabilities, consider that today's DNA screening technologies require that DNA samples be amplified using polymeric chain reaction, or PCR, techniques in order to get sufficient signal to noise levels. In addition, the reaction between the sample and test chip, the hybridization process, can take many hours to complete. The biocompatible, nanomagnetic technologies being developed in the BioMagnetICs Program offer the potential to greatly reduce the time to identify DNA because the sensitivity afforded by magnetic sensors may eliminate the need for PCR, and magnetic forces can be used to significantly increase the hybridization rate. Ultimately, this may make identifying humans via their DNA as fast, simple, and economical as current fingerprinting techniques.

With that, I conclude my discussion and thank you for your attention.