DARPA

DSO40

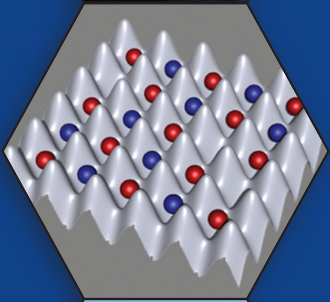
Years of Innovation

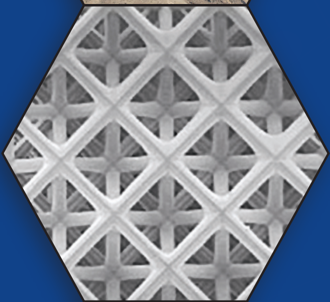
1980–2020

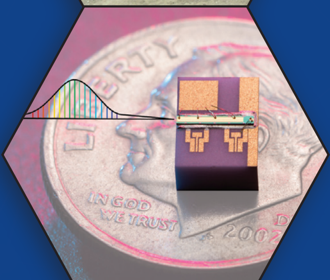
DEFENSE SCIENCES OFFICE

DSO40

1980–2020







DSO: Forging New Scientific Frontiers for 40 Years

Dr. Valerie Browning
Defense Sciences Office (DSO)
Office Director

Four decades ago, DARPA (then ARPA) decided to combine several offices focused on singular technologies into one office that could represent the breadth of sciences needed to support the DARPA mission. That office, the Defense Sciences Office (DSO), is now DARPA's longest running, continuously staffed office. Over these past forty years, program managers (PMs) in DSO have worked to change what's possible in support of national security. DSO PMs serve as DARPA's far forward scouts, identifying and seeding new foundational science and technology upon which future generations of pivotal, breakthrough technology can be built. From creating entirely new disciplines to spinning off new DARPA offices, DSO has helped shape and reshape the national security technology landscape.

What are the secrets to DSO's success in consistently expanding and redefining the art of the possible? There is no singular answer to this question, but much of what makes DSO work can be attributed to the strength of diversity and collaborative culture that permeates the office.

DSO is by far the most diverse DARPA office in terms of our people and our programs. DSO PMs are known for their insatiable passion and curiosity and often seek to leverage the breadth of expertise and experience of their colleagues in building portfolios designed to have positive impact on national security. In fact, many DSO programs emerge at the intersection of two or more disparate disciplines, e.g., materials with computer science, robotics, and biology; chemistry with AI; and math with just about everything. DSO's groundbreaking contributions in prosthetics, quantum information science, armor, functional materials, and biowarfare defense are just a few examples of DSO innovating across multi-dimensional seams between various disciplines.

A collaborative, supportive, and respectful culture is essential and a core strength within DSO. The generation of new programs and the identification of new Office directions are very much "all hands on deck" endeavors. Spirited debate, while an important part of the new start development process, is always conducted in a respectful and constructive manner. One PM's success at getting a new program approved is celebrated by the entire office, and when a PM struggles, his or her colleagues will step up to help. Preserving this collaborative culture with a constant rotation of extraordinarily talented and technically diverse PMs has been, and continues to be, one of the highest priorities for DSO leadership in recruiting new PMs. It is perhaps the most challenging, and yet most rewarding, role for the Office Director and Deputy Director.

DSO: Forging New Scientific Frontiers for 40 Years (cont'd)

Today, DSO's role in supporting the DARPA mission is as important as it has ever been. In a world of proliferated technology and global competition, we continue to scour the far horizons of the technology landscape for opportunities to forge new scientific frontiers. Beyond the breadth of innovation pursued across multiple scientific disciplines, DSO looks for novel approaches to fundamentally accelerate DARPA's R&D acquisition processes. For example, DSO's rapid acquisition Disruptioneering program served as the model for similar programs including MTO's MicroExploration and the Agency-wide AI Exploration programs. A willingness to challenge the norm, pursue non-traditional concepts, and encourage "out-of-the-box" thinking when it comes to all aspects of innovation are further examples of strengths that have contributed to DSO's many successes over the years.

"...many DSO programs emerge at the intersection of two or more disparate disciplines, e.g., materials with computer science, robotics, and biology; chemistry with AI; and math with just about everything."

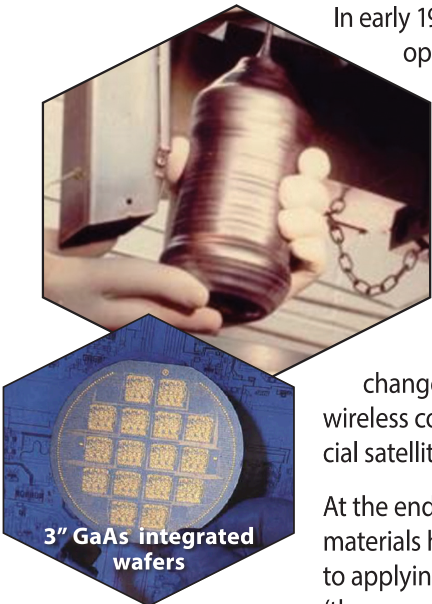
The following pages include a collection of articles that highlight examples of DSO innovation throughout its 40-year history. The articles are organized by decades. DSO's early roots and contributions in materials and manufacturing are a focus of the 1980s articles. In the 1990s section we see the emergence of biowarfare defense as a DARPA focus area as well as the very early beginnings of several multi-decade technology development arcs in functional materials and mathematics. Articles in the early 2000s section highlight important DSO investments in structural materials, robotics, and prosthetics. Our 2010s articles bring us to current times where we see DSO's deliberate move to invest in the social behavioral sciences and to leverage advances in AI and data analytics for everything from fundamental advances in materials, manufacturing, and chemistry to city scale monitoring and deterrence of WMD/WMT threats. Finally, DSO's current Deputy Director, Dr. Phil Root, will take a look into the future and speculate on how DSO will continue to serve as "DARPA's DARPA" over the next 40 years!

We hope you enjoy this look back across the DSO innovation timeline.

Gallium Arsenide Devices

During its first ten years as an office, DSO invested in a wide range of electronic materials, spanning the exploration of conductivity of inorganic crystals to the development of new compound semiconductors. These early investments in electronic materials made a significant impact on the electronic materials community, advancing new capabilities in both commercial and military applications.

One area in which DSO played a pivotal role was the development of fabrication technologies needed to establish gallium arsenide (GaAs) devices. GaAs devices promised many advantages compared to silicon-based technology: they were predicted to consume a fraction of the power, operate at much higher speeds, function over a wide temperature range, and be much more resistant to radiation damage. Although DARPA did not invest in the early development of GaAs as a semiconductor material, it did fund seminal work to develop and demonstrate some of the first GaAs devices based on field-effect transistors with a Schottky barrier. In the early 1970s, before DSO was an office, DARPA's investments were focused on developing ion implantation techniques for GaAs devices that led to the demonstration of ion-implanted gallium arsenide metal-semiconductor field-effect transistor logic gates. In the early 1980s, DSO continued this work, initiating programs that enabled the development of Microwave and Millimeter-Wave Monolithic Integrated Circuits (MIMIC). In addition, DSO established a GaAs IC pilot line program to move the technology out of the laboratory and into manufacturing.



Gallium Arsenide boule (top), that will be sliced and polished into 3" wafers for processing (bottom)

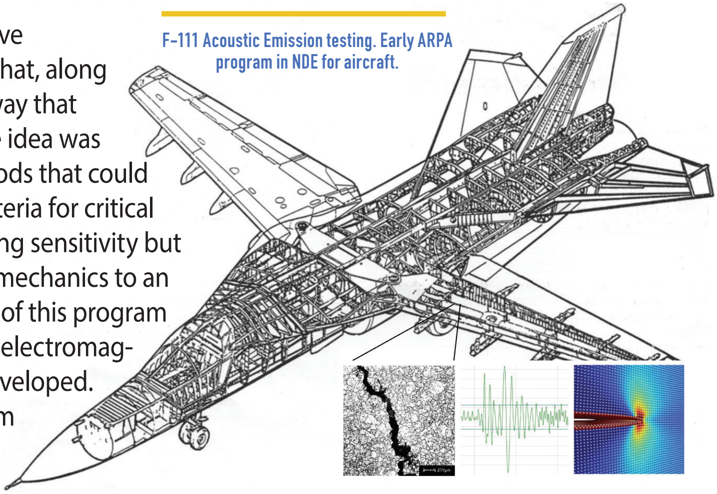
In early 1988, DSO initiated a new program to insert digital (GaAs) ICs into eleven operational weapon systems to improve performance over silicon-based devices. These systems included a distributed-array processor for special-mission (reconnaissance) aircraft, a spacecraft on-board processor for reconnaissance satellites, a digital radio frequency memory for the AN/ALQ-136 jammer, and a radar processor for E-2C airborne early warning aircraft.

DSO's foundational work in developing fabrication technologies to build GaAs devices ushered in new capabilities that not only significantly impacted the performance of military systems, but also changed our daily lives. New technologies based on GaAs devices include wireless communications, GPS, and collision-avoidance radar as well as commercial satellite communications.

At the end of DSO's first decade, it was evident that the field of electronic materials had grown enough to support a standalone technical office devoted to applying these technologies, and the Electronics Technology Office (ETO) (the precursor to today's Microsystems Technology Office (MTO)) was spun out of DSO. However, even after the formation of ETO, DSO continued to fund basic research in electronic materials, which included the development of Wide Bandgap Semiconductor Technology and High Temperature Superconductors for military applications.

Nondestructive Evaluations – Retirement for Cause

Imagine if every year you threw away all of your clothes because 0.1% of them were expected to be unwearable. That was exactly the case for jet engine turbine disks in 1980, where, because 1 failure out of 1000 from low-cycle fatigue was expected after a set number of cycles, all of the disks were taken out of service—even though 99.9% of the disks were still perfectly good. Although there was research on nondestructive approaches to find the cracks that led to this failure, the efforts were focused on increasing sensitivity; there was no work that related flaws in a material to the actual lifetime of the part that would solve this problem.



F-111 Acoustic Emission testing. Early ARPA program in NDE for aircraft.

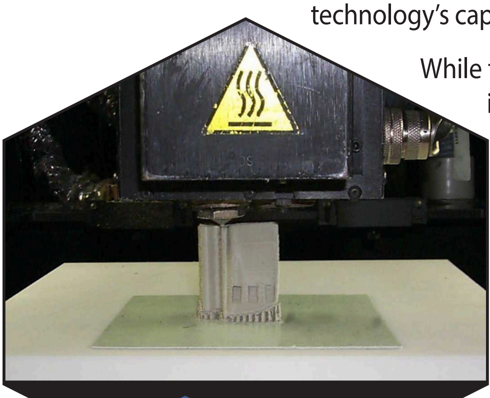
This issue was the genesis for the quantitative Nondestructive Evaluation (NDE) program that, along with its follow-on programs, changed the way that critical military systems are maintained. The idea was to develop/demonstrate quantitative methods that could provide a rational basis for accept/reject criteria for critical aircraft parts. This required not just increasing sensitivity but linking the found defects through fracture mechanics to an actual prediction of part lifetime. The focus of this program was primarily on ultrasonic techniques, but electromagnetic and acoustic approaches were also developed. One of the primary successes of the program was to connect world class experts in fracture mechanics to fundamental studies of signal propagation. The program made NDE a viable university research area, encouraging some of the world's most prominent material scientists and physicists to participate in the program.

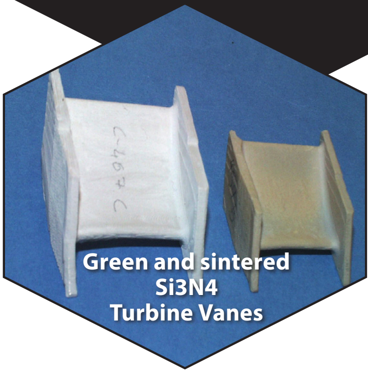
The immediate transition of this program was to the Retirement for Cause (RFC) program in the late 80's. That concept allowed each disk to be used to the full extent of its safe total fatigue life, with retirement occurring only when a quantifiable defect necessitated removal of that particular component from service. The defect size at which the component is no longer considered safe was determined through fracture mechanics analysis and the service cycle. This program was adopted for the U.S. Air Force (USAF) F100 engine by the USAF Air Logistics Command's San Antonio Air Logistics Center, with a total of 23 fan, compressor, and low pressure turbine rotor parts managed under this philosophy.

The DSO work in NDE and RFC paved the way to Condition-Based Maintenance, a widely accepted strategy that monitors the actual condition of an asset to decide what maintenance needs to be done. NDE also was the precursor to DSO's Prognosis program, which began in 2001 with the goal of determining remaining usable life and the quantitative prediction (prognosis) of the future operating capability of critical components.

Solid Freeform Fabrication

Although additive manufacturing captured the public's attention in the 2010s, it's been around for nearly 40 years, with DSO making some of the pivotal early investments. To reduce fabrication development times, DSO's early seedling programs developed the foundational knowledge and equipment for "tool-less" manufacturing and integration of design and fabrication tools. Annual symposia on Solid Freeform Fabrication (SFF) began at University of Texas at Austin in 1987 and marked the emergence and growth of the field from the subspecialties of topography and photosculpture. Early investments by DSO moved SFF from simply laminating 2D patterned layers to more conventional 3D printing with the advent of its Solid Freeform Fabrication program in 1990. SFF removed usual manufacturing constraints imposed by cast, drilling, and milling and fostered a deeper synergy between design and fabrication. This enabled the creation of one-off prototypes for rapid evaluation and incorporation of changes, which stands in sharp contrast to conventional manufacturing processes, e.g., die making. The capacity to manufacture complex 3D geometries with the same level of effort as simple geometries opened the door to realizing the true potential of fabricating complex 3D parts. The development of additive manufacturing was not easy, and DSO consistently pushed the boundaries of additive manufacturing with follow-on programs that expanded the material suite available for 3D printing as well as new processes that expanded the technology's capability base.





Fused deposition systems builds a conformably cooled silicon nitride turbine blade

While the core development of additive manufacturing occurred in the late 1980s and early 1990s—and paved the way for the 3D printing we know today—DARPA broadened the aperture of advanced manufacturing with targeted investments in the 2000s and 2010s to increase the precision and types of materials available as well as ways to rapidly incorporate additive-manufactured components. DSO's Mesoscopic Integrated Conformal Electronics (MICE) program enabled direct writing of passive electronics. The Rapid Vaccine Assessment programs developed the technology to print biomedical materials and tissues for the rapid evaluation of potential vaccines. The Make-It program is enabling the direct automated manufacturing of chemicals on demand.

Other DSO programs looked beyond manufacturing using different materials to consider different scales of additive manufacturing. In the Materials with Controlled Microstructural Architecture (MCMA) program, recent advances in additive manufacturing were exploited to enable microscale architecture fabrication to improve the structural efficiency of materials and enable properties that exceed or are

Solid Freeform Fabrication (cont'd)

not even possible with bulk materials. Programs such as Atoms to Product (A2P) focused on developing scalable digital manufacturing techniques with nanoscale precision across centimeter or larger volumes to further enhance the precision and scalability of additive manufacturing.

"The capacity to manufacture complex 3D geometries with the same level of effort as simple geometries opened the door to realizing the true potential of fabricating complex 3D parts."

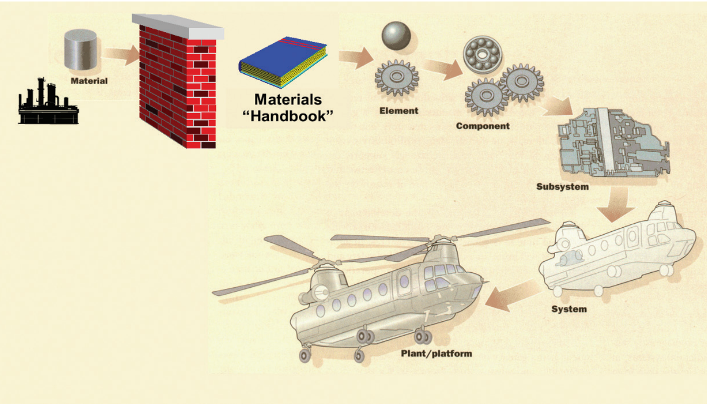
While several DARPA investments developed and advanced additive manufacturing materials and precision, others worked to use additive manufacturing to solve delays inherent in the acquisition process. The Advanced Rapid Response Manufacturing (ARRM) program created technologies to rapidly manufacture components for current or emerging needs to overcome the challenges of acquisition. The Open Manufacturing program enabled the rapid qualification of new technologies for the manufacturing environment through the development of new modeling and informatics tools to expedite the incorporation of new components in response to DoD needs.

DSO investments are playing a key role in enabling the additive manufacturing of multi-material systems (e.g., ceramics with metals) that will have significant impact on the performance and readiness of DoD platforms.

Accelerated Insertion of Materials

Through its creation and funding of the Interdisciplinary Laboratories in 1960, DARPA essentially gave birth to the field of Materials Science and Engineering as we know it today. From that point on, DARPA has focused on developing new and improved materials to meet new mission performance requirements as well as support existing ones by improving size, weight, and power (SWaP) while decreasing cost.

Since its founding in 1980, one of DSO's key missions has been to continue making discoveries relative to new materials. Early achievements resulted in materials that enabled high performance jet engines, lightweight aircraft and ships, satellites, and even ceramic body armor.



AIM sought to address the disconnect between materials development and system design where materials are developed empirically and tossed "over the wall" to the system designers.

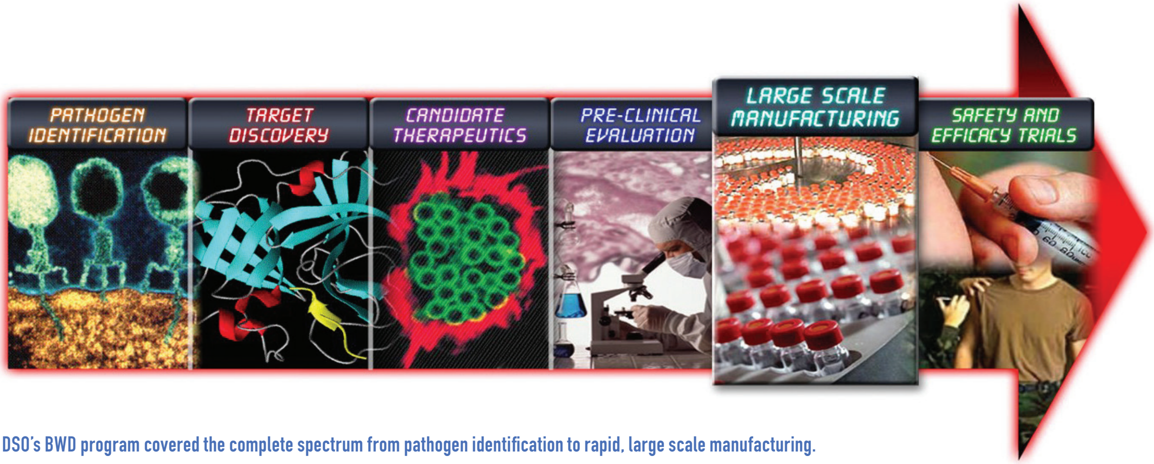
However, DSO's achievements from the 1980s were not enough to keep pace with advances made in manufacturing and design in the 1990s. New engines could now be designed in 30 months, but development of the new material required to optimize those engines still took 3–4 times as long. This mismatch forced engine designers to use existing, well-characterized materials, making insertion of new materials almost impossible. In response to this dilemma came DSO's Accelerated Insertion of Materials (AIM) program. The concept of AIM was to integrate system design into the development of a new material right from the start and, at the same time, increase the use of computation and experimental design to shortcut the extensive trial and error materials qualification process. AIM sought to manage the uncertainty of using a new material, thus allowing designers to make informed choices about how a new material might behave.

By linking computational materials tools and process design space to develop optimal compositions and processing for a given application, AIM formed the basis for the paradigm-shifting concept of Integrated Computational Materials Engineering (ICME). ICME embodied the precepts of AIM, forming a fundamental pillar of material science and engineering that provided approaches for tremendous reduction in the cost and time-consuming experimentation that normally paces the materials development cycle. ICME spawned the White House Office of Science and Technology Policy's (OSTP) Materials Genome Initiative, which continued the paradigm shift in how new materials are discovered, developed, and deployed. AIM also paved the way for a new generation of DSO programs in manufacturing and design in the 2010s, such as Open Manufacturing, that would continue to revolutionize the use of materials in DoD platforms.

Biowarfare Defense

On July 30, 2020 The Washington Post published an article entitled "How a secretive Pentagon agency seeded the ground for a rapid coronavirus cure." That "secretive agency" was, of course, DARPA, and the office that started it all was DSO. Flash back to April 1997 when, stimulated by a Richard Danzig seminar, Captain H. Lee Buchanan, USNR, published "Poor Man's A-Bomb," in the Proceedings of the Naval Institute, an article focused on how DoD might deal with biological weapons. Since Dr. Buchanan was also the director of DSO, he brought his ideas to the DARPA director, and the DSO Biowarfare Defense (BWD) effort was on the verge of being born. There was once hiccup. Congress mandated that all BWD efforts be managed by the DoD Chem-Bio Defense Program. In order for DSO to begin the BWD effort, DARPA had to seek legislative permission to run an independent program, which was granted in the FY98 National Defense Authorization Act. At that point, the DSO BWD program was off and running.

From the start, the BWD program was focused on approaches that were not tied to specific pathogens. For example, the Unconventional Pathogen program was designed to break the one-bug, one-drug paradigm. The Tissue Based Sensor program had the goal of creating sensors that would warn of harmful agents without being tuned for any in particular. Another effort, Rapid Vaccine Assessment, was among the first to use living tissues as a way to screen the deleterious effects of therapeutics, thus eliminating early failures without animal trials. It was also the first demonstration that tissues could be printed by additive manufacturing, a technology that has been used extensively since. Another major effort, Accelerated Manufacture of Pharmaceuticals, increased the responsiveness of pharmaceutical production to new BW threats by using novel production platforms such as plants. These programs were followed by efforts designed to get ahead of natural or engineered diseases. For example, the Prophecy program sought to predict viral evolution in order to make therapeutic development proactive. And in 2011, the Autonomous Diagnostics to Enable Prevention and Therapeutics (ADEPT) program was started. ADEPT was a broad technology program aimed at providing options for preempting or mitigating constantly evolving infectious disease threats. Pioneering nucleic-acid-based anti-infective technologies were developed under this effort.



DSO's BWD program covered the complete spectrum from pathogen identification to rapid, large scale manufacturing.

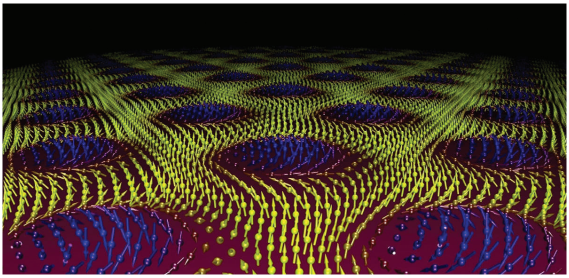
Biowarfare Defense (cont'd)

DSO through its BWD program recognized there was a high likelihood that the U.S. and its military would need to react quickly to poorly understood or perhaps totally unknown threats – something that has proven important in several global health crises. For example, in response to the H1N1 influenza outbreak in March of 2009, DSO put in place the Blue Angel program portfolio designed to identify and characterize the H1N1 virus. This effort also established the capability to manufacture millions of vaccines via the deployment of multiple novel expression platforms (plants, fungi, etc.) to augment traditional manufacturing methods. Technologies from DSO programs were also employed during both the Ebola and Zika crises.

The BWD program moved to DARPA's Biological Technologies Office (BTO) after its split from DSO in 2014, where BTO continues applying novel approaches to deal with BW threats. This has enabled DARPA to effectively support the COVID-19 pandemic, with technologies such as ADEPT's DNA- and RNA-encoded medical countermeasures against infectious disease proving their worth. However, as The Washington Post article indicates, "If it weren't for DARPA's investments over the past decade and earlier… the American race toward a vaccine and antibody therapy to stop the coronavirus most likely wouldn't be moving as quickly as it is today." There can be no greater compliment for what DSO began decades ago.

Spintronics

Many of the advances in computing memory made over the last 25 years can be traced back to DSO's Spintronics program. Begun as the Magnetic Materials and Devices (MMD) program in 1995, Spintronics, which is a portmanteau for Spin Transport Electronics, exploited the discovery in 1988 of giant magnetoresistance (GMR), a quantum mechanical magnetoresistance effect observed in multilayers composed of alternating ferromagnetic and non-magnetic conductive layers. The resistance in the conducting layers depends on the orientation of the magnetic spins in the adjacent ferromagnetic layers—low resistance when they are parallel, high when they are not. The Spintronics program took this effect and combined it with newly discovered magnetic tunnel junctions, where quantum mechanical tunneling of electrons magnified the GMR effect. This allowed the development of high-density memory devices based on magnetic control of spin orientation.

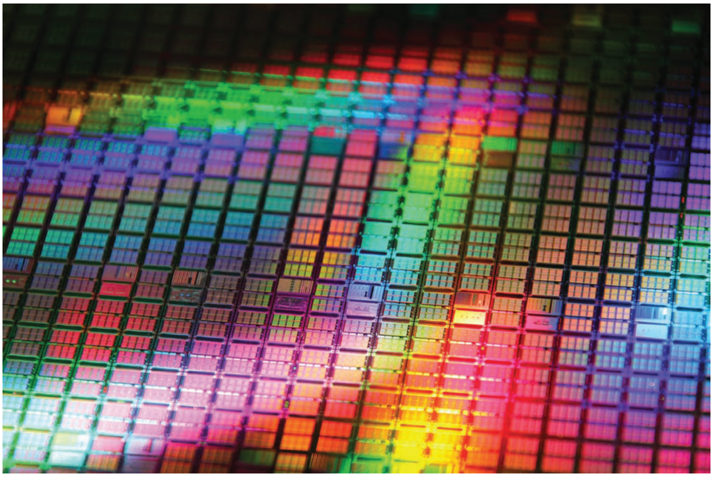


Through control of magnetic spin orientation, Spintronics enabled high density, rad hardened memory devices.

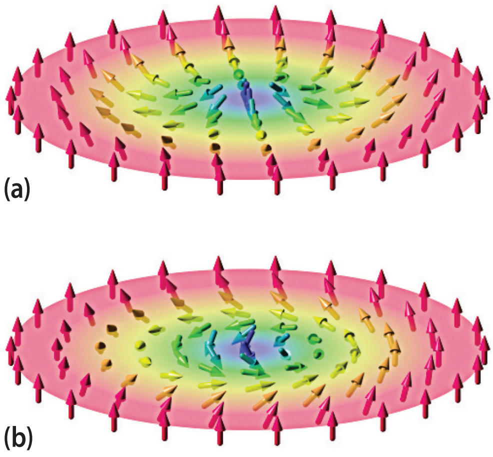
The rapid development of magnetic memory by the Spintronics program coincided with DoD's need for rad-hard memories for its satellites and missiles. The existing plated wire memory weighed 40 lbs., had only 128 kB memory, cost $250K per memory device, and was susceptible to single-event upsets. By contrast, the development of GMR under Spintronics

Spintronics (cont'd)

made possible a memory with storage based on magnetic spin rather than charge, allowing the memory to be retained when the computer/storage device was turned off. The result was a rad-hard memory for space applications that was several orders of magnitude smaller in size and power consumption than systems that were being deployed and had the speed of static random-access memory (SRAM) (<3ns) and the density of dynamic random-access memory (DRAM) (up to 4 Gbit). This work led directly to the popularization of magnetoresistive random-access memory (MRAM), which is a mainstream non-volatile memory for both commercial and defense applications.



Spintronics was the progenitor of DSO's Spins in Semiconductors (SPINS) program begun in 1999. SPINS sought to modify the magnetism at room temperature of an electric field and to exploit the ability to optically induce magnetism in a semiconductor. The success of SPINS pointed to the possibility of manipulating spins in semiconductors to create quantum bits or qubits, contributing to DSO's explorations in quantum computing, including the Quantum Information Science and Technology (QUIST), Quest for Undiscovered Energy Storage and Thrust (QUEST), Quantum-assisted Sensing and Readout (QUASAR), and, most recently, Driven and Nonequilibrium Quantum Systems (DRINQS) programs.



TOP: Wafers bearing spintronics technology, like this colorized specimen from Everspin Technologies, host a multitude of magnetoresistive random access memory (MRAM) dies before these are diced and packaged into individual MRAM chips. ABOVE: Skyrmions are vortex-shaped multi-electron structures that flip states only as a unit, bestowing them with more stability compared with simpler electron organizations

DSO's Topological Excitations in Electronics (TEE) program, begun in 2017, marked a return to DSO's investments in Spintronics. TEE explores the topological protection of electron spins in the recently discovered magnetic state of the skyrmion to offer a new tuning capability in magnetic materials with implications for very high-density memory storage.

Pivotal Investments in Foundational Mathematics

In the early 1980s, DARPA was investing in substantial, concerted architecture-, hardware- and software-related research efforts, but no similar funding existed for the pivotal mathematical research needed to benefit from these advances. The lack of large-scale, forward-looking investments in math meant that potentially paradigm-shifting mathematical work went unfunded. Against this backdrop, Professor Louis Auslander persuaded the DARPA Director that it was in the DoD's interest to change the status quo, and DSO's Applied and Computational Mathematics Program (ACMP) was born.

ACMP sought to expedite fundamental mathematical developments that might plausibly result in radical advances in capability. ACMP projects were multi-disciplinary with the goal of developing effective mathematical representations and fast, scalable algorithms. Projects in ACMP's formative years evolved naturally into four thrusts: 1) architecture-aware algorithmic representations, 2) exploitation of structure in data, 3) analysis-based fast algorithms, and 4) prediction, design, and control of physical systems.

Architecture-aware algorithmic representations. Novel computer architectures generally facilitate programming models and automation tools that maximize performance and programming productivity. Nonetheless, for critical applications, hand tailoring of algorithms and code is often needed to address low-level machine considerations. In this thrust, DSO math projects pioneered novel multidisciplinary computer science and engineering research that resulted in entirely new software engineering automation technologies and accelerated adoption of new classes of computer architectures. The archetypal ACMP project under this thrust used architecture-aware representations of fast Fourier transform (FFT) algorithms to systematize performance tradeoffs. A subsequent project, Signal Processing Implementation Research for Adaptable Libraries (SPIRAL), formulated the automatic generation of high-performance implementations of FFTs and other algorithms as an optimization problem and solved it by combining computer algebra representations with machine learning search methods. The resulting architecture-aware "compiler" concept inspired high performance computer vendors like Intel to move from hand-coded scientific libraries to machine-generated libraries for a broad class of related algorithms, resulting in dramatically reduced costs and increased productivity. ACMP efforts inspired an MTO project demonstrating that graphics processing units (GPUs) provided a quantum leap in signal processing capability. The associated technological developments helped facilitate the GPU's ubiquity in present-day computers.

Exploitation of structure in data. For many DoD-relevant digital technologies such as signal/image processing and communications, processing demands always exceed current computing technology, and any shortfall is exacerbated by suboptimal algorithms and small-footprint requirements. This ACMP thrust brought to bear several previously untapped bodies of mathematics, including "wavelet analysis," to produce novel means of leveraging structure present in objects of interest. Over the next few decades, DSO projects resulted in revolutionary advances in approach and technology in areas that include data processing and analysis, signal and image processing, waveform and filter design, navigation, digital photography, and analog-to-digital system design. Developments under ACMP led to standards for

Pivotal Investments in Foundational Mathematics (cont'd)

wavelet compression of digital imagery, which is now widely used for compression of fingerprints, medical images, and general still images and motion capture.

Analysis-based fast algorithms. A significant barrier to effective use of large-scale computational resources in the 1980s for simulating physical phenomena in applications such as electromagnetics, quantum chemistry, and gravity was the dearth of accurate, scalable algorithms. ACMP projects exploited the Fast Multipole Method (FMM) to develop analytical machinery for efficiently representing certain multi-scale physical phenomena, and the underlying methodology has revolutionized a broad swath of computational science, making virtual test beds possible where, for example, the electromagnetic scattering for an aircraft model can now be computed in hours as opposed to days in the 1980s. Projects under ACMP also resulted in widespread advances in analysis-based fast algorithm technology in applications including automated optimal filter design, gravitational field calculations, and quantum chemistry (QC).

Prediction, design, and control of physical systems. In the late 1980s, complex dynamics, irreversibility, and disparate physical and temporal length scales of materials processes were significant obstacles to designing high-yield, cost-effective processing strategies. Modeling and simulation were widely used in many areas of physical science and engineering, and control theory was well-established in many commercial industries. However, the state of the art at the time was woefully inadequate for many materials systems of DSO interest. Two notable 1990s DSO projects were Rapid Thermal Processing (RTP) and Virtual Integrated Prototyping (VIP), which were instrumental in successful design, scale up, and control of materials processes involved in the fabrication of atomic-scale transistors and electronic materials. As transistors shrank, RTP was used to shorten thermal cycles in wafer-processing furnaces in order to reduce defects. For the first time, equipment makers could simulate closed-loop RTP equipment performance to efficiently make and evaluate design changes. The resulting dynamic real-time control software is used in most semiconductor fabs. VIP developed a novel level set method for modeling film growth and morphology, which has become standard for epitaxial growth. VIP also led to the design and prototyping of an entirely new method of film growth, target biased ion beam deposition (BTIBD), that rapidly produces ultra-smooth films of metals and oxides as well as integrated atomistic-to-macroscopic computer models suitable for controlling thin-film deposition for giant magnetoresistance (GMR)-derived materials, enabling a quantum leap in GMR use commercially and in DoD products.

The technical accomplishments achieved under ACMP resulted in major advances to the state of the art in many technical fields. The approach of integrating mathematics with science and engineering pioneered by ACMP beginning in the 1980s is still pursued by DSO today in programs such as Enabling Quantification of Uncertainty in Physical Systems (EQUiPS) and Lagrange.

Legs Matter

Cockroaches on a treadmill…a YouTube video of the Big Dog robot with millions of hits…the world's speed record in legged robotics—this is the legacy of DSO's biomimetic robotics program. These were all part of DSO's Controlled Biological Systems (CBS), a program that began with the notion that, in order to successfully navigate the world, biological species have refined movement and sensing. While there were several interesting offshoots of the sensing thrust, it was the emulation of biological mobility that got the most focus. As part of this effort, the seminal article, "Wing Rotation and the Aerodynamic Basis of Insect Flight," was the cover article of the 18 June 1999 issue of Science. Another effort studied how geckos climbed walls, which ultimately led to the very successful Z-Man program. But it was the development of legged robots that ultimately proved to be of most value to DoD.

Big Dog" robot was developed as a "mule" to traverse difficult terrain.

The ability of legs to efficiently maneuver in terrain where wheels and tracks were ineffective was well known. While there were some early attempts to copy the way biology uses legs, most research focused on computer calculations of the positions of legs, a task that required sensing the environment before moving a leg—hardly an emulation of biology. To understand the difference, think about what happens when one is running on grass and then encounters sand. One can feel how the legs adapt a new gait to maintain stability in the new environment. While there is a complicated kinematic explanation for how the leg motion adapts, the bottom line is that biology does these "calculations" not by thinking about leg placement, but through the way the legs and joints are constructed. The CBS program set about to see if this could be replicated in robots, hence, the study of cockroaches going over rubble on a treadmill to understand the dynamics of their legs.

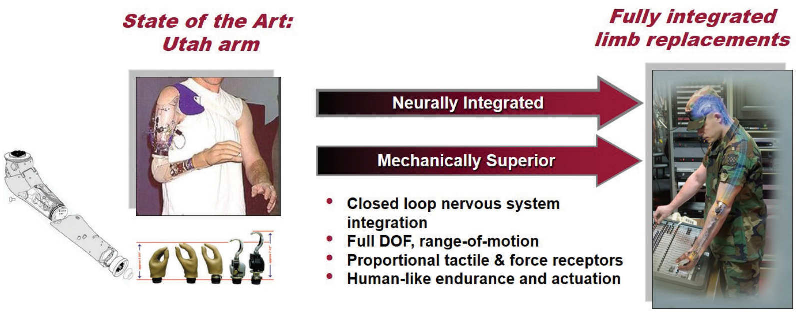
From these early studies came a series of legged robots including, RHEX, a hexapod that could successfully traverse complicated terrain. This was followed by Big Dog—a four-legged, headless robot that became a YouTube sensation because of its ability to stabilize itself while traversing disparate surfaces, climb steep rubble piles, and even recover from a swift kick. Big Dog transitioned to TTO's Legged Squad Support System (LS3) program, which conducted further development and demonstrations with the Marine Corps. In 2014, the "robo-mule" was featured in RIMPAC field tests with the Marine Corps, in which the quadruped robot carried 350–400 pounds of gear over difficult terrain and demonstrated its autonomous capabilities.

Although the LS3 effort did not become a program of record because of the engine noise, the legacy of DSO's program has had a significant impact in the design of legged robots. Inspired by the technical achievements made to enable LS3, DSO initiated a new program called Maximum Mobility and Manipulation (M3) to create and demonstrate robots with improved mobility and manipulation capabilities that mimicked those of fast-running animals in nature. Under M3, a robot called "cheetah" was clocked at over 28 mph—faster than Usain Bolt!

DSO-developed robot technologies also enabled the TTO-managed DARPA Robotics Challenge. While competitors in the 2015 final competition were not required to field a robot with legs, legs proved useful for three of the eight required tasks: driving a vehicle, maneuvering over a rubble pile, and climbing a ladder, demonstrating again that legs do matter.

Revolutionizing Prosthetics

"At DARPA, we have the vision of a future where a soldier who has lost an extremity in battle will regain full use of that limb again…If they could play the piano before, they will play the piano again." These words, spoken by DSO Program Manager Colonel Geoffrey Ling, USA, at the 2005 DARPATech, announced the Revolutionizing Prosthetics program, a program designed to design, develop, and prototype truly revolutionary upper body prosthetics. Dr. Ling described this as a pact we have made with those who "wake up every morning to protect and serve American ideals."



Keeping the pact we have made with those who wake up every morning to protect and serve American ideals.

Advances in body armor were truly a life saver, but as a consequence, many warfighters returned home with lost limbs. While the loss of a leg is tragic, lower body prosthetics had by this time made great strides, even enabling competitive running. Yet, despite the importance of the arm and hand to everyday life, the best prosthetic arms available at the time were powered by gross muscle movements, the most functional hand little different than a hook. The aim of the Revolutionizing Prosthetics program was to design an upper extremity prosthetic that used breakthroughs in actuation, mechanical power distribution, energy storage, biotic/abiotic interfaces, sensors and computation, and, most importantly, had the ability to control the arm and hand by the intent of the user.

The promise of harnessing the brain to control movement stemmed from a significant fundamental research investment by DSO starting in 1999 aimed at understanding how the brain encodes signals that represent the intent to move a limb. In the Human Assisted Neural Devices program, researchers were able to decode those signals and send them to a robotic arm controlled by the brain. This work was demonstrated in non-human primates and, in a few cases, in humans. Since then, development of more advanced decoders has allowed co-adaptation between the system's algorithms and the user's neural activity, which further accelerated a user's mind-based motion control.

Today the DEKA Arm System, which is the same shape and weight as an adult arm, has been approved by the FDA and is a commercial product. It has 10 flexible joints, controlled by input devices such as surface electromyography (EMG) electrodes. Currently 23 people living with arm amputations, including 12 veterans, have received the arm systems. Meanwhile, work on full brain control prosthetics continues in BTO with research participants living with paralysis using the direct brain interfaces to feed themselves and to directly control a flight simulator with brain signals.

The advances made in upper body prosthetics by the Revolutionizing Prosthetics program prove that the pact Dr. Ling and DSO made with our warfighters in 2005 is well on its way to being fulfilled.

Wasp

The operational success of the Wasp micro air vehicle and its follow-on platforms belies the fact that the concept began in 2003 as one idea within DSO's Synthetic Multifunctional Materials program (SMFM). SMFM explored the advantages of integrating structure with function in DoD systems.

The original concept for Wasp was to use a specially developed fiber battery as the structural member of the wing, thereby avoiding the parasitic weight of a separate battery pack. Without the extra battery weight, the initial Wasp design improved endurance, made way for more nimble avionics, and increased payload capacity. The success of the concept was demonstrated through record long flights that drew the attention of the Marines, who were looking for a highly portable ISR platform technology for beyond-line-of-sight visual surveillance at the squad and individual warfighter level.

The engagement with the Marines, combined with the urgency of the Middle East conflict, rapidly moved Wasp from a materials program into a field-demonstrated, prototype platform. To meet warfighter operational requirements, WASP was redesigned, and DSO moved away from the "structural battery" concept in favor of a more conventional and operationally supportable configuration incorporating a separate battery pack. The next generation Wasp was a hand- or bungee-launched, fixed-wing UAV that weighed less than a pound and fit in a backpack. It could fly in excess of 35 mph with complex payloads and a sophisticated autopilot enabling hands-free operation so that the operator could focus on the mission and obtain the necessary tactical imagery. By virtue of its extremely small size and quiet propulsion system, Wasp provided unobtrusive, real-time imagery from low altitudes. Wasp Block III became the first micro air vehicle adopted by the U.S. Armed Forces in support of a Program of Record (formally announced January 2008).

Wasp Block III

A US Army Staff Sergeant throwing a Wasp III.

Materials to Protect Our Warfighters

DARPA has a long legacy of developing technologies to protect U.S. warfighters on the battlefield from the ever-present threat of bullets and blast. Over the last two decades, ballistic and blast threats for both mounted and dismounted soldiers have become a relentless problem due to the ease in improving bullet and blast lethality through advancements in materials.

DSO's early investments in armor focused on understanding the fundamental physics that describe how materials used for protection behave during high dynamic loading. These early investments began to reveal the role of individual material properties (e.g., hardness, ductility, elastic limit) along with the collective behavior of combinations of different materials in determining the observed ballistic behavior. This early understanding of material properties allowed designers of armor solutions to integrate different materials with dissimilar properties to produce a ballistic protection solution that offered greater survivability than the sum of its individual material layers.

U.S. troops in the Afghanistan and Iraq wars benefited from these early DSO investments in materials development and computational modeling for ballistic protection. These advancements contributed to the development of boron carbide body armor inserts that provided significant improvement in protection against armor piercing rounds. In addition, the boron carbide inserts provided a 35% reduction in weight over the existing alumina-based inserts and became the armor of choice in the Army Interceptor Body Armor system.

Underbody explosion test (10x over SOA) on an blast resistant vehicle integrated with a multi-level energy absorbing system allowing all of the occupants to survive with minimal injuries.

Materials to Protect Our Warfighters (cont'd)

DSO investments in ultra-lightweight armor pushed the development of computational tools for body armor and enabled the community to use modeling and simulation rather than just "shoot-and-look" for determining ballistic performance. Furthermore, these tools allowed for the design of body armor systems that provided multi-hit protection with minimal increase in armor weight. DSO continued to improve body armor solutions by advancing the development of Ultra-High Molecular Weight Polyethylene (UHMWPE) ballistic fabrics that offer improved energy absorption and enhanced protection over Kevlar at reduced weight. In conjunction with the fabric development, DSO supported the improvement of computational tools to assist in understanding how these fabrics, along with their architecture, behaved under high dynamic loading. Improvement in these tools and the new fabrics developed under this program have been integrated into the Army's Generation II Soldier Plate Carrier System, which provides the best survivability performance against today's as well as emerging ballistic threats.

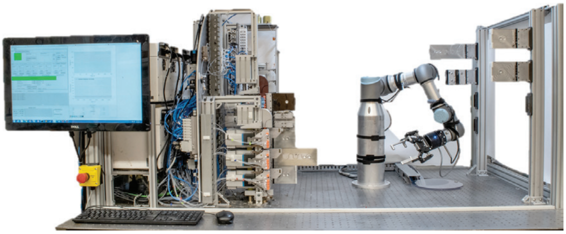
In the early 2010s, mounted soldiers in the Middle East were experiencing an increase in the lethality and variety of blast threats encountered in-theater. The initial military vehicles deployed in the Middle East had minimal underbody protection from IEDs, which our advisories discovered and successfully exploited. The initial military solution to protect the vehicle occupants was to add more vehicle armor, resulting in substantial increases in the weight of tactical vehicles that impacted maneuverability, off-road use and maintainability. During this period, DSO initiated several vehicle protection programs to address the countervailing requirements of protecting the warfighter from increasing threat levels, while maintaining desired levels of mission effectiveness. DSO leveraged breakthroughs in shock physics, materials science, energy conversion, and armor mechanics to develop energy dissipation/conversion mechanisms for improved armor designs and underbody blast mitigation. The successes of these programs enabled new energy management systems, where the entire structure of the vehicle is involved in absorbing and dissipating the underbody blast energy. Currently, the DSO technology is being incorporated into future military vehicle systems to protect soldiers from IEDs with blast outputs over seven times greater than the protection afforded by current SOA fielded protection systems.

As part of the vehicle protection programs, DSO supported the development of new transparent ceramic armor window systems. This effort achieved a transparent armor solution capable of stopping 30 caliber armor piercing threats at 50% of the weight of the current Army SOA. In addition, solutions were found that survived multi-hit threats at 37% of the SOA weight. These transparent windows are now being evaluated in the Army's Ultra-Light Vehicle (ULV) program.

DSO's enduring support of protecting the soldier on the battlefield has provided a new level of protection against advanced threats, allowing our soldiers to be more mobile and less vulnerable. Through these investments in developing new armor and blast mitigation technologies, DSO has been instrumental in increasing the number of warfighters who return home safely.

Make-It

When chemists look to create new molecules, they traditionally rely on their expertise, intuition, and a time consuming, trial and error process to discover the proper production method (i.e., "recipe"). When they want to reproduce a known molecule, they rely on a recipe developed and shared by another chemist. Much as for the home cook, this recipe doesn't always work out as planned. Variations such as how fast a reaction is stirred or slightly different temperature conditions can significantly impact purity and yields.



This system, built by Make-It researchers at MIT, can synthesize chemicals without any manual intervention by a human. First, AI software selects the best reactions to make a given molecule, then a robotic arm configures the system to carry them out.

In 2015, DSO began the Make-It program to leverage concepts from computer science, organic chemistry, and chemical engineering to automate recipe design, molecule production, and optimization in an attempt to standardize the creation and production of molecules for DoD. Efforts in the program are building software tools based on machine learning and expert-encoded rules to recommend synthetic routes and enable robotic execution of those routes to eliminate the need for chemists to physically handle dangerous chemicals, making for a safer, cleaner, and more secure process. Automating molecule creation and discovery also standardizes reproducibility of results.

With Make-It, chemists may focus their energy on chemical innovation rather than on the tedious and repetitive tasks involved in testing various molecular synthesis pathways. Additionally, chemists and non-chemists alike are able to create molecules on demand in their own laboratories in custom-sized quantities rather than buying molecules in bulk from a chemical supplier and disposing of the excess.

Make-It research teams have recently demonstrated significant progress toward fully automated rapid molecule production, which is speeding the pace of chemical discovery for a range of defense products and applications, including, but not limited to, pharmaceuticals, energetics, and coatings. These accomplishments include the release of several software tools for chemical synthesis planning (one commercial, one open source, and one in closed testing); demonstration of automated synthesis in continuous flow cartridges, traditional chemistry glassware, and 3D printed reactors; and a system for testing chemical reactions at an unprecedented rate (>5,000 per hour).

Additionally, the COVID-19 pandemic has magnified weaknesses in the global pharmaceutical supply chain related to production of both active pharmaceutical ingredients (APIs) and the key precursors used to synthesize them. In response, Make-It is developing an integrated end-to-end (feedstock to finished medicine) domestic manufacturing platform for the production of critical medicines. Through CARES Act funding provided in response to the COVID-19 pandemic, a Make-It performer recently successfully synthesized chemical precursors using widely available starting materials and continuous manufacturing technology. The precursors were subsequently used to synthesize an analog of an API given to COVID-19 patients in intensive care.

Manufacturing, Function, and Design

Developing and manufacturing low-volume, high-value systems is expensive and time consuming. Many high-valued defense systems have suffered from extensive delays and cost escalation during testing and early production due to difficulties incurred in the course of manufacturing key components and subassemblies. Moreover, despite large investments in and extensive testing of components, many military platforms have encountered unanticipated problems, even when they are deployed as designed. The inherent nature of military systems, i.e., the low numbers of units produced, is the culprit in many of these failures. Low parts volume provides limited statistics regarding the cause of part variability and how this variability impacts the performance of the final component. Such uncertainty leads to a reluctance to insert new, innovative manufacturing technologies.


Additive manufacturing links and fittings for the engine nacelle of the V-22 Osprey

DSO's Open Manufacturing (OM) program fundamentally changed how variability in manufacturing is captured and controlled by creating a manufacturing framework that accounts for factory-floor variability and integrates probabilistic computational tools, informatics systems, and rapid qualification approaches to build confidence in manufacturing processes.

OM's tools and manufacturing framework were used to address manufacturing and design issues with the gun turret on the Mine Resistant Ambush Protected (MRAP) ATV. The gun rotor accounted for a large fraction of the weight on the MRAP. Produced from ballistic steel and requiring significant fabrication time, the rotor was very heavy, which caused excessive wear problems and made the vehicle top-heavy. OM's solution was to fabricate the rotor out of a lightweight material, Ti-6Al-4V alloy. OM demonstrated the use of additive manufacturing with coupled thermal mechanical simulation to minimize thermal distortion during the build, which significantly impacted post-process machining costs. The result was an advanced, lightweight turret design that reduced the overall turret weight by hundreds of pounds.

More recently, Open Manufacturing's approach has inspired new DSO programs aimed at revolutionizing the entire concept of function and design. For example, Fundamental Design (FUN Design) and TRAnsformative DESign (TRADES) are developing the foundational mathematics and algorithms to solve "the inverse problem in design." These programs are aimed at enabling designers to first specify the performance values for a system and its parts—whether it is a missile, ground vehicle, or prosthetic limb—and then hand those off to computational and modeling tools to generate multiple solutions that balance shape with the detailed material structures that could deliver the performance and functionality required by the design specifications.

If successful, FUN Design and TRADES would fundamentally change the relationship between humans and computers, making the computers true partners in design rather than tools that record a human's decisions and act like a large calculator. The designer would be responsible for stating the intent of the

Manufacturing, Function, and Design (cont'd)

design and setting up the problem formulation, and the computer would explore and present to the user the viable design options. The DSO vision is that these efforts will result in new computer systems that can design things we can't even currently imagine! By harnessing computing power within a design framework, DSO's manufacturing and design programs have revolutionized the way DoD will design, manufacture, and qualify its future military systems.

SIGMA

From its inception DSO has pursued programs in nuclear threat detection. During the Cold War, technology developed by DSO was used in early efforts to detect nuclear tests. In the aftermath of the breakup of the Soviet Union and the attacks on 9/11, the threat of terrorist attacks involving the use of proliferated radiological and special nuclear materials has posed a potentially grave threat to U.S. citizens and service members. Early detection of these materials and devices made from them became a critical part of the U.S. strategy to prevent such attacks.

In 2016, DARPA worked with D.C. Fire and EMS for approximately seven months to demonstrate the potential of SIGMA. Almost 40 ambulances were outfitted advanced radiation sensors that provided the first city-scale, dynamic, real-time map of background and anomalous radiation levels throughout the Capital, depicted above.

In 2014, DSO's SIGMA program rose to meet this challenge by pursuing new, networked nuclear and radiological detection technologies, with the goal of achieving low-cost, high-performance radiation detectors with spectroscopic gamma and neutron sensing capabilities. SIGMA achieved city- and region-scale search capability through an integrated program aimed at personal, stationary and vehicle-mounted detectors networked to advanced cloud architectures designed to maximize sensitivity and reduce false alarms to an acceptable level. The widespread availability of cheaper and more efficient detectors permitted CONOPs that were previously simply not viable from either cost or operational perspectives. The result was that the radiation detection capability of the system as a whole exceeded that of the individual parts operating independently.

SIGMA officially transitioned to the Port Authority of New York and New Jersey, providing advanced radiation threat detection at key locations in the greater New York City area. SIGMA has also transitioned to Federal partners within the DoD and DHS. Lastly, SIGMA sensors and networking capabilities are now available as commercial products.

The unparalleled success of SIGMA led to the follow-on SIGMA+ program, which is developing new sensors and networks that would alert authorities to illicit chemical, biological, and explosives threats as well.

DSO's SIGMA and SIGMA+ programs are key enablers to protecting both military and civilian personnel worldwide from terrorist attacks across the weapons of mass destruction threat space.

Quantifying Social Science

Understanding how humans interact with their world is an incredibly complex and multidimensional problem – but it is key to how the DoD plans and conducts effective military operations, including humanitarian aid, disaster relief, and stability support missions as well as tactical, operational, strategic, and policy-level decision-making. Unlike with the physical sciences that are governed by immutable natural laws, the social sciences are complicated by the fact that humans operate with free will and are, therefore, not subject to such rigid guiding principles. Despite this challenge, DoD has been trying to "quantify" the social sciences for the past several decades. Such efforts include DoD's Human Social Culture Behavior (HSCB) modeling program and Minerva Research Initiative and even an early DARPA entry, Integrated Crisis Early Warning System (ICEWS), each with some degree of success. However, it was DSO's view, backed up by many studies, that the social science research foundation on which these programs was built was shaky at best.

DSO research seeks to quantify social science.

For example, social science researchers would routinely change their research hypotheses to fit the results. Modeling and simulation capabilities for the social sciences were rudimentary and often disconnected from causality. There was also no agreed-upon framework to ensure reproducibility and replicability of research, so there was no way to determine which research results decision makers should rely on.

To ameliorate these problems, DSO created a series of social science programs, each designed to address one or more of these weaknesses in social science research.

The Next Generation Social Science (NGS2) program, approved in 2015, began to address fundamental flaws in social science research by providing researchers with methods and tools that enable new capabilities for rigorous, reproducible, experimental research. A key transition from this program has been pre-registration of efforts, which has now been adopted widely within the research community, including DARPA. Other important transitions from NGS2 include adoption of study design tools, platforms, and methods by DARPA, other government customers, nonprofits, and the commercial sector to facilitate study recruitment and reproducibility of research results.

Quantifying Social Science (cont'd)

DSO's Ground Truth program used artificial but plausible social simulations with known causality or "ground truth" that other performers must discover using their own methods. The goal is to create a social science "wind tunnel" to test the explanatory and predictive accuracy and robustness of a wide range of social science modeling methods. In addition to advancing social simulation capabilities, Ground Truth enables DoD and researchers to better evaluate which modeling methods provide the most relevant understanding of social complexity relevant to a wide range of DoD missions. Metrics developed under the program for comparing complexity across simulations and against real-world systems have been adopted by the RAND Corporation, which is researching measures of complexity in wargames.

Systematizing Confidence in Open Research and Evidence (SCORE) is developing approaches that will allow users to automatically quantify the amount of confidence they should have in any given social science claim. SCORE is combining scalable methods to collect and validate expert assessments of social science research with machine learning advances to identify and aggregate many weak signals to automate expert assessments and establish quantitative standards of confidence in social science research. SCORE is also formalizing definitions for reproducibility and replicability.

With these and other DSO social science programs in place to shore up the fundamentals of social science research, DSO is moving toward programs that exploit these fundamentals to achieve specific operational value to DoD. The first of these programs, Habitus, is designed to aid operational decision making in under-governed regions by creating methods for generating causal system models based on local knowledge.

Although DSO's social science programs are relatively new in the context of DSO's 40 year history, they are already reshaping the face of social science research and empowering DoD to better plan for and conduct its military operations.

DSO–What's next?

Dr. Philip Root
Defense Sciences Office (DSO)
Deputy Director

Legged locomotion to spintronics? The preceding articles tell the DSO story from inception to today, and I would like to briefly share some thoughts on possible future impacts. There are groundswells of beyond-SOA discoveries happening in DSO within the physical sciences related to materials science, atmospheric science, quantum technologies, cognitive science, AI, and physical chemistry that all deserve additional attention. However, I would like to elaborate on the topic of "cyber-social systems."

Unlike cyber-physical systems which exist at the intersection of multiple domains including electrical, mechanical, and computer science, cyber-social systems exist at the nexus of individual behaviors, social norms, and the digital domain. While cyber-physical systems face a unique set of engineering and security challenges as they blur the distinction between mechanical design and algorithmic augmentation, cyber-social systems must embrace the additional complexity associated with including individuals, teams, and societies within the system boundary. Pure computer science can be accused of ignoring the role of the human within the operation or larger system, a shortcoming that research into cyber-social systems must centrally address. I foresee the arc of cyber-social systems as one of the several possible significant technical impacts arising from DSO.

I propose that cyber-social systems have at least three eigenvectors: computing that is for the people; computing that is with the people; and computing of the people. Let's address the first eigenvector. Individuals are hard to study and impossible to predict, but computing to support individuals requires approaches that incorporate humans centrally by design. This is a foundational issue for DoD; Western democracies underline the central importance and responsibility of the human, Soldier, Sailor, Airman, and Marine. For these Warfighters to maintain responsibility and agency for their actions, computing must be built that respects human challenges such as our attentional limits and biases but also leverages our strengths of innovation, broad contextual understanding, rich language, and rapid grasp of complexity. DSO sees the need for programs that develop new frameworks for human-machine systems engineering with joint concepts of agency and attention.

To address the second eigenvector, we already see autonomous systems and algorithms joining people in joint ventures. To compute with the people requires new concepts for teaming, communication, innovation, problem solving, and trust. Performing all the above in high risk environments with limited time for consensus and coordination will doubtlessly inform applications for hybrid teams operating in military intelligence cells, factory floors, and corporate boardrooms. Western society thoroughly studies and respects the ethical, legal and social implications of any new policy or technology. Computing that is with the people must be compliant with societal norms, but this requires a degree of contextual understanding far in excess of current capabilities. Contextual understanding whether within combat

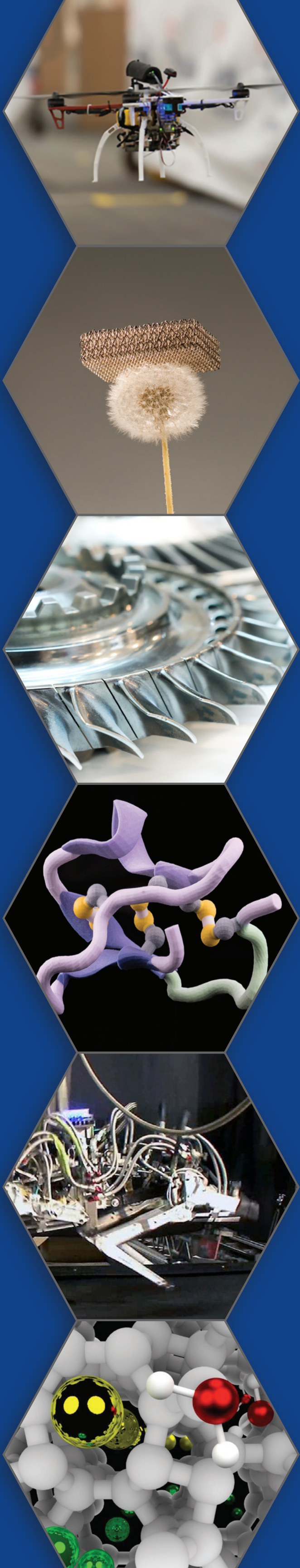
DSO–What's next? (cont'd)

or civilian applications requires not only the understanding of the larger context but also of broader purpose or intent. Under what conditions is it appropriate to provide autonomous systems and AI instantiations with the initiative to perform the mission without further guidance? DoD must achieve thought leadership in this area to maintain the public trust DoD has earned while increasing capability overmatch.

Finally, computing of the people comprises social media, scientific peer review, and online economies where individual actions and responses create a fabric of social connection and group dynamics. This fabric is neither good nor bad, but technologies can make the most of this fabric when we develop robust social science tools and models to understand group biases and actions. Next generation social and behavioral sciences research must balance experimental anthropology that might discover deep but unnoticed human biases through research into normative approaches to societal issues.

"...computing must be built that respects human challenges such as our attentional limits and biases but also leverages our strengths of innovation, broad contextual understanding, rich language, and rapid grasp of complexity."

DSO is uniquely situated to lay the foundation for such an arc of cyber-social systems. Early work in complex, adaptive systems supports mathematical modeling of social settings. Ongoing rigorous social science has led to tools that support future, unforeseen research needs in near real time. Current artificial intelligence programs are deeply rooted in math and science and address such non-traditional topics as trust and surprise. I submit that DSO has a unique opportunity and perspective standing on the shoulders of these past and current programs to peer into the future horizons of computing for the people, with the people, and of the people.



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This booklet that memorializes the accomplishments of DSO over the last four decades was made possible by the efforts of the following individuals:

Greg Byerly
Julie Evans
Kristen Fuller
Heather Heigele
Stephen Ryan
Randall Sands
Adrian (Chip) Smith
Anna Tsao
Steven Wax

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