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CREATE: Accelerating Defense Innovation With Computational Prototypes and High Performance Computers

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Abstract

Today, rapid innovation in product development is essential to be competitive in any field. It is true for DoD acquisition as well as everyone else. To investigate the potential for computational prototypes and High Performance Computing (HPC) to enable product innovation in DoD acquisition programs, the U.S. Department of Defense HPC Modernization Program (DoD HPCMP) Office initiated the Computational Research and Engineering Acquisition Tools and Environments (CREATE) Program in 2006 (Post et al., 2016). The CREATE goal is to develop and deploy physics-based HPC software applications for the design and analysis of military air craft, ships, and radio frequency antenna systems (and more recently ground vehicles) to enable DoD acquisition programs to improve acquisition outcomes through the construction and analysis of virtual prototypes for those systems. Development of the software applications began in 2008. Ten years later, the CREATE software tools are already beginning to enable DoD engineering organizations (government and industry) to accelerate the rate of innovation in major defense systems, and reduce the cost, time, and risks of acquisition programs for those systems. One aspect of this paradigm is that it enables the DoD to employ features of the Silicon Valley culture that facilitate rapid product innovation.

Introduction

The enabling, disruptive technology that enables accelerated innovation through the use of virtual prototypes is the rapid growth of high performance computing over the last 60 years. Since the end of World War II, the calculating power of computers has grown exponentially from ~1 Floating Point Operation/second (FLOP/s) to over 10^{16} FLOP/s

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(http://www.top500.org/). This means that—for the first time in history—it is possible to make accurate predictions of the behavior of many, many complex physical systems (e.g., the weather, chemical systems, airplanes, ships, automobiles, etc.). We can now develop and deploy science-based software applications for high performance computers that

1. Include the major physical effects that determine the performance of the system,
2. Utilize highly accurate mathematical and numerical solution algorithms,
3. Are verified and experimentally validated,
4. Can predict the performance of a full-scale system (e.g., an entire ship or airplane),
5. Enable multidimensional design of experiments to generate large trade-spaces for a full scale system, and
6. Can complete a high-fidelity, time-dependent, three-dimensional multi-physics calculation for a maneuvering system in a few days that took weeks in 2005, and months (if even possible at the same level of fidelity) in 1995.

This capability enables design engineers to construct realistic virtual prototypes of physical systems (ships, microprocessors, earth moving equipment, etc.) and make accurate predictions of their performance by solving the physics equations that govern their behaviour.

In the past, it was necessary to construct real prototypes for these systems and use live tests to assess their performance and find the design flaws. With simple systems, and incremental changes, there was time in the past to follow the traditional product development paradigm of "design, build, test, fail, re-design" iterated cycles that had proved so successful since the beginning of the industrial revolution. For the standard system engineering product development process (Kossiakoff & Sweet, 2003; see Figure 1), the design of new products is based on "rule of thumb" extrapolations of existing products. Sub-system physical prototypes are developed and experimentally tested during the engineering design phase, and full system physical prototypes are developed and tested just before and during full scale production. With today's more complex weapon systems such as fighter airplanes, aircraft carriers, tanks, submarines, and so forth, these live tests occur too late to provide timely data on design defects and performance shortfalls. Expensive and time-consuming rework is required to fix the problems uncovered by live testing. The DoD 5000 acquisition process (Carter, 2013) is very similar to the standard systems engineering product development process depicted in Figure 1.

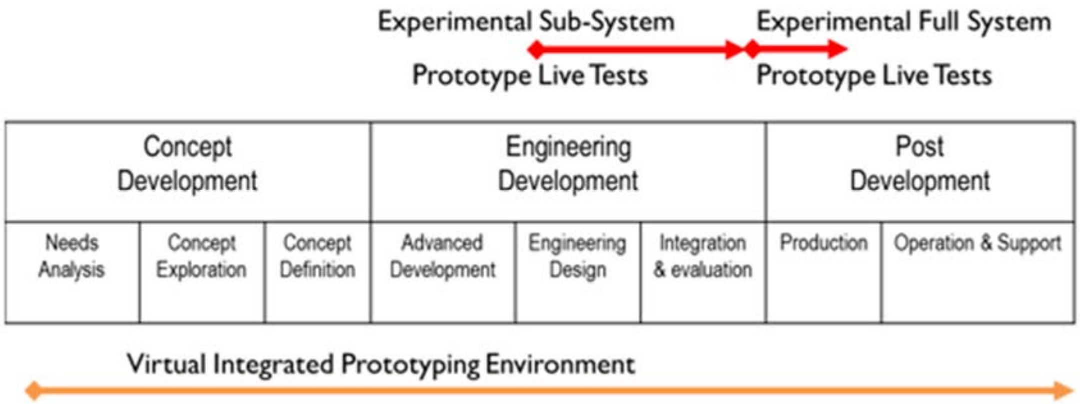

Figure 1. System Engineering Product Development Life Cycle Model
(adapted from Kossiakoff & Sweet, 2003)

The effective use of virtual prototypes requires a high performance computing ecosystem consisting of the appropriate software applications, supercomputers, and a high speed network to connect the users to the supercomputers. For the DoD, that ecosystem is provided by the U.S. DoD HPC Modernization Program (HPCMP) Office, which supplies high-performance computing resources to the Science and Technology, Test and Evaluation, and Acquisition Engineering communities of the Armed Services and DoD agencies. The HPCMP Office provides continuous modernization of five DoD Supercomputing Resource Centers (DSRCs), the network that connects them (DREN), and the associated physics-based simulation software applications in response to prioritized needs of the Services. Recognizing the need to help spur innovation for major defense systems, the HPCMP Office in 2006 launched the Computational Research and Engineering Acquisition Tools and Environments (CREATE) Program. CREATE was chartered to reduce the cost, time, and risks of DoD acquisition programs by developing and deploying multi-disciplinary, physics-based software applications for the design and analysis of military air craft, naval ships, and radio frequency antenna systems by DoD engineering organizations. In 2012, the scope of CREATE was expanded to include ground vehicles.

Using the CREATE tools, engineers can construct virtual prototypes and computationally analyze product performance at any stage of the development process, supplementing or substituting for data from live tests. For conceptual design of new systems, “rule-of-thumb” extrapolations of existing designs can be replaced with physics-based generation of design options allowing extensive trade-space exploration, and rapid assessment of the feasibility and advantages of all the design options with physics-based analysis tools. These engineers can consider many thousands of design options instead of a few. For detailed design development, high-fidelity analysis of virtual prototypes can replace “failure data from live tests” with “physics-based accurate predictions of virtual prototype performance” to drive design iteration and innovation. As the design matures, the digital model can be matured accordingly in terms of completeness of geometry and governing physics. Live tests can then be used to validate the final designs. This provides timely decision data that enables engineers to identify design flaws and performance shortfalls early, allowing problems to be fixed before metal is cut and minimizing rework that cause schedule delays and cost growth. The tools can be applied at all stages of the product development process, from early concept design through operation, support, sustainment, and modernization (Figure 1).

CREATE code development began in 2008, and 10 years later, CREATE is beginning to accomplish those goals. The CREATE tools are being used by more than 160 DoD engineering organizations (50% government, 40% industry, and 10% other) for the assessment of more than 70 DoD acknowledged weapon systems and platforms. There are over 1,400 active CREATE user software licenses, and the number of users is continuing to increase.

The CREATE tools can also help make the testing process more productive, more effective, and more efficient. The tools can be used to identify the most sensitive and uncertain operating conditions so that testing programs can concentrate on those areas, allowing the total test data requirements to be reduced a factor of five or more with a concomitant reduction in the required testing time (Kraft, 2010). In addition, it frees the testing community to address the basic scientific and engineering issues that determine weapon system performance as well as enabling a much greater number of test events with the existing test facilities. The software allows the DoD Test and Evaluation (T&E) community to rehearse testing events and design the test experiments.

Many industries and federal agencies have successfully adopted the virtual prototype paradigm (Council on Competitiveness, 2010; Francis, 1995; Miller, 2010) to obtain a competitive advantage in their market place. Until recently, however, there has been little public information on the value of the paradigm, chiefly because it gives organizations that use it a significant competitive advantage, and their use of the paradigm is considered a trade secret. A few examples are publically available. The Partnership for Advanced Computing in Europe (PRACE) established an Automotive Simulation Center (ASC) in Stuttgart, with projects in vehicle drive, vehicle structure, vehicle physics, and so forth. ASC director, Alexander Walser, noted in 2014 that “numerical simulation made its way in the design phase of automotive development and productions (as) a useful tool for faster problem analysis and reduction of cost and product design time” (Walser, 2014). Specific benefits, however, were not detailed. In an aerospace industry example, however, Doug Ball, then Boeing’s chief engineer for enabling technology and research, stated, “When we were designing the 767 back in the 1980s, we built and tested about 77 wings. By using supercomputers to simulate the properties of the wings on recent models such as the 787 and the 747-8, we only had to design (*and test*) seven wings, a tremendous savings in time and cost” (Ball, 2009).

Starting in 1992, Goodyear developed a physics-based design tool for tires that became the core of their “innovation engine” (Miller, 2010). Goodyear CEO Richard Kramer noted in the Q4 2010 Earnings Call, “Our *innovation engine* again delivered in 2010. The percentage of new products in our overall lineup is the highest ever. … Our innovative new products continue to accumulate an impressive list of test wins and third-party endorsements” (Kramer, 2011). In the *2009 Annual Report,* then Goodyear CEO Robert Keagan stated that “Our new product engine is poised to take advantage of the demand for high-value-added tires and to do so with unmatched speed to market” (Keagan, 2010, pp. 2–3). With this approach, Goodyear reduced its product development time from three years to as little as eight months and reduced its new product prototyping and testing costs from 40% to 15% of the R&D budget, an annual savings of $100 million (Engardio, 2008).

The CREATE Program

CREATE code development began in 2008 as a set of four projects (Air Vehicles, Naval Ships, Radio Frequency Antennas, and Meshing and Geometry). A fifth project was added in 2012 for Ground Vehicles. Combined, the projects are developing and deploying 11 individual software applications (Table 1). The choice of the projects was dictated by the relative size and importance of major defense acquisition programs and the potential for HPC and physics-based software applications to predict the performance of associated systems.

The CREATE projects have two types of software products: (1) concept development tools (viz., DaVinci, RSDE/IHDE, a module of SENTRi, and MAT) to generate conceptual designs and analyze their feasibility and performance using fast, but lower-fidelity analytics; and (2) high-fidelity, multi-disciplinary tools (Kestrel, Helios, NESM, NavyFOAM, SENTRi, and Mercury) to provide accurate predictions of the system performance. The Meshing and Geometry project is subordinate to the other four CREATE projects and provides capability for concept design tools to generate numerical representations of the platform and then to generate the meshes needed for computational analysis. The Meshing and Geometry tool (Capstone) can also produce meshes from geometry representations generated by the most commonly used commercial CAD tools. Capstone provides a numerical representation of the geometry of the weapon system of interest, a digital prototype of the weapon system.

The CREATE tools have been developed, deployed, and supported by the DoD (DoD employees and contractors). They are validated with DoD experimental data for DoD use cases, and are "owned" by the DoD. The DoD has government purpose distribution rights to all of the CREATE software. The CREATE tools give DoD acquisition program engineers the ability to make independent assessments of proposed designs and contractor deliverables. In this role, the tools are directly helping the DoD acquisition engineering community grow its organic engineering capability, a DoD priority for technical workforce development.

The Eleven HPCMP CREATE™ Software Applications

CREATE Air Vehicles

DaVinci—Concept Design Tool for Air Vehicles

DaVinci will allow engineers to populate design option spaces of fixed and rotary wing aircraft and provide an initial assessment of the performance of the design. Choosing from previously engineered components, the tool will allow engineers to select and modify wings, fuselage, and propulsion components. Aircraft designers then can select, adjust, and rearrange internal components in aircraft designs. It is "Model Centric." It will support highly efficient construction and maintenance of air vehicle models, including geometry that is parametric and includes water-tight external geometry, internal structure, subsystem layout, volumes, and mass properties. It will provide a multi-disciplinary, physics-based analysis capability that is variable fidelity, but is consistent across disciplines. It provides the ability to persist design data and intent throughout acquisition and program life. The virtual model can be tested virtually through its flight envelope to assess basic performance characters, including mission performance, and decision support with uncertainty quantification and sensitivity analysis.

Table 1. CREATE Projects and Products

Projects	Products
Air Vehicles (CREATE-AV)	DaVinci (Rapid conceptual design)
	Kestrel (High-fidelity, full-vehicle, multi-physics analysis tool for fixed-wing aircraft)
	Helios (High-fidelity, full-vehicle, multi-physics analysis tool for rotary-wing aircraft)
Naval Ships (CREATE-SH)	Rapid Ship Design Environment (RSDE; Rapid Design and Synthesis Capability)
	Navy Enhanced Sierra Mechanics (NESM; Ship Shock & Shock Damage Assessment)
	NavyFOAM (Hydrodynamic-predict hydrodynamic performance)
	Integrated Hydro Design Environment (IHDE; Facilitates hydrodynamic performance evaluations in early stage ship design)
RF Antennas (CREATE-RF)	SENTRi (Electromagnetics antenna design integrated with platforms)
Ground Vehicles (CREATE-GV)	Mercury (physics-based tool for M&S of terrain mechanics and vehicle systems and components. Incorporates suspension, tire and track, soil modeling, and powertrain simulation)
	Mobility Analysis Tool (MAT; converts physics-based vehicle performance data and terrain information into mission-based analysis of performance over large areas of terrain)
Meshing & Geometry (CREATE-MG)	Capstone (Components for generating geometries and meshes needed for analysis)

The current version of DaVinci (V3.1) has the capability to build parametric designs for fighter, transport, and surveillance aircraft that include the Outer Mold Line (OML) and structural envelope. It supports geometric analysis including areas, volumes, centroids and moments, and high fidelity aerodynamic analysis using the high-fidelity tool Kestrel. It can design and build a geometric model of a platform, and build a mesh that captures this geometry with Capstone for high fidelity analysis with Kestrel. Surrogate geometry models have been built for the support of the KC-46, the new Air Force Tanker based on the Boeing 767, and the Joint Surveillance and Target Attack Radar System (JSTARS).

Kestrel—High-Fidelity Tool for Fixed Wing Air Vehicle Performance Prediction

Kestrel has the capability to provide accurate predictions of the performance of DoD air vehicles, with a specific focus on the fixed-wing community. It integrates computational fluid dynamics, structural dynamics, propulsion, and control for sub-sonic through supersonic aircraft operation. In detail, the capabilities available in Kestrel v5.0 include (1) Aerodynamics (Navier-Stokes solvers and a full suite of boundary conditions and turbulence models), (2) Structural Dynamics (Modal models or Finite Element Analysis for aero-structure interactions), (3) Flight Control Systems (Control surface movement—deforming geometry or overset), and (4) Propulsion (Engine "cycle-decks" for propulsion effects, or direct engine simulation including inlet and rotating machinery, nozzle, and moving walls).

This set of capabilities is unique in the international aerospace community. It provides the capability to develop major innovations in the design of next generation aeronautical weapon systems. With Kestrel, engineers can verify designs prior to key decision points (and prior to fabrication of test articles or full-scale prototypes), plan and rehearse wind-tunnel and full-scale flight tests, evaluate planned (or potential) operational use scenarios, perform flight certifications (e.g., airworthiness, flight envelope expansion, mishap investigation, etc.), and generate response surfaces usable in DaVinci, flight-simulators, and other environments that require real-time access to performance data. Kestrel has been applied to the analysis of over 30 fixed-wing DoD aviation systems including store separation, A-10, F-18E, F-15, B-52, E-2D, P-3, and many others. Dr. Theresa Shafer, an engineer at the Patuxent River Naval Air Station, was awarded the American Society of Naval Engineers (ASNE) 2014 Rosenblatt Young Naval Engineer Award for her career accomplishments, including her work using Kestrel to produce flight certification and airworthiness data for seven small unmanned aerial vehicles that enabled seven small aerospace companies to bid on NAVAIR development contracts.

Helios—High-Fidelity Tool for Rotary Wing Air Vehicle Performance Prediction

Helios is a high-fidelity, full-vehicle, multi-physics analysis tool for rotary-wing aircraft. Helios v5.0 can calculate the performance of a full sized rotorcraft, including the fuselage and rotors. It can handle arbitrary rotor configurations (e.g., conventional main rotor/tail-fan, co-axial main rotor/pusher propeller, tandem main rotors, tiltrotors, quad-tiltrotors, etc.). It has the capability to analyze and predict prescribed maneuvers with tight coupling of rotor aero-structural dynamics. A highly accurate treatment of the vortex shedding from the rotor blade tips using adaptive mesh refinement gives Helios a unique capability to assess the interaction of these vortices with the fuselage and nearby rotor blades. Helios can provide all the benefits for rotary-winged aircraft that Kestrel can for fixed-wing aircraft.

There have already been important examples of the use and value of Helios. The Army Rotorcraft Program (AMRDEC/AED) used Helios with Boeing to generate early design stage predictions of helicopter performance for a proposed rotor blade upgrade for the CH-47F helicopter (Chinook) to achieve up to an estimated 2,000 pounds improved hover thrust for 400+ Chinooks with limited degradation of forward flight performance. The Army Joint-Multi-Role Technology Demonstrator (JMR-TD) Program used Helios to provide decision data on the proposals from four vendors for the JMR-TD program. Helios enabled government engineers to provide the government the ability to conduct an independent analysis of the contractor proposals. The Army Rotorcraft Program (AMRDEC/AED) is using Helios to assess the H-60 tail rotor effectiveness for providing directional control of aircraft in combination with increased engine power and main rotor performance.

CREATE Ships

RSDE—Rapid Ship Design Environment (Rapid Concept Design for Ships)

RSDE is a concept design tool that allows engineers and naval architects to assess the tradeoffs inherent in designing ships to meet a spectrum of competing key performance parameters. Employing the concept of design space exploration, engineers and naval architects can provide data for decision makers on the impact of tradeoffs in range, speed, armament, aviation support, etc. on the size and, in large measure, the cost of a proposed ship concept. RSDE can generate tens of thousands of candidate ship designs with varying hullforms, subdivision, and machinery arrangements. An initial assessment of the intact and damaged stability and resistance, and an initial structural design and analysis is done for each candidate ship design. RSDE has been used to enable set-based design (Singer, Doerry, & Buckley, 2009) on Navy acquisition programs. This design method allows down-selection of a ship design to occur later in the process when the tradeoffs are more fully understood. It has been applied to numerous ship design studies including the Amphibious Landing Craft LX(R) Analysis of Alternatives, and the Small Surface Combatant Trade Study. Dr. Adrian Mackenna, the team leader for the RSDE tool, was awarded the 2014 American Society of Naval Engineers (ASNE) Gold Medal for his work developing and applying the RSDE tool.

NESM—Navy Enhanced Sierra Mechanics (Ship Shock & Shock Damage Assessment)

NESM builds on the Department of Energy's Sandia National Laboratory shock analysis tool Sierra Mechanics to provide a means to assess ship and component response to external shock and blast using accurate high performance computational tools. NESM can reduce the time and expense required for physical shock testing of ship classes and also improves the initial ship design process by assessing planned component installations for shock performance prior to final arrangement and installations decisions. The tightly coupled multi-physics capabilities include (1) Structural Dynamics (Implicit linear-elastic solver: static, modal, transient, acoustics, and more), (2) Solid Mechanics (Explicit plasticity solver: failure, high-strain, multi-grid, and more), (3) Fluid Dynamics (Euler solver: shock propagation, load environments, and threat modeling), and (4) Fluid-Structure Interaction. The solution algorithms in NESM can exploit massively parallel computers, and can scale to thousands of cores, enabling efficient computer use and the ability to address full-sized naval vessels up and including next generation aircraft carriers and submarines.

NESM will materially contribute to the design of next generation naval weapon systems and platforms, support planning and rehearsal of ship tests prior to Life Fire Testing (more "bang" per test dollar), and the evaluation of planned (or potential) operational use scenarios. NESM has been officially adopted by the Navy for these uses. "The NAVSEA Technical Warrant (for Shock/Ships) concurs that NESM is the appropriate and technically acceptable modeling and simulation (M&S) tool which meets the M&S requirements to support current and future surface ship shock applications." NESM was previously approved for "Full Ship Shock Trials (FSST) Alternative R&D Programs (PEO Ships & PEO Carriers)," which led to the release of OPNAVINST 9072.2A, providing future ship classes with an alternative to Full Scale Shock Trials. NESM has been used to support Littoral Combat Ship (LCS) Live-Fire Test & Evaluation (LFT&E) and the USS *Cole* Validation Study, and to provide support for Live Fire Test and Evaluation for the Navy's next generation Nuclear Aircraft Carrier (CVN-78 and 79). Dr. Thomas Moyer, the NESM team leader, was awarded the ASNE 2015 Soldberg Award for his pioneering research modeling shock effects in naval systems, including leading the NESM team.

NavyFOAM—High Fidelity Predictions of Ship Hydrodynamic Performance

NavyFOAM is based on the OpenFOAM (http://www.openfoam.org) libraries and code architecture. To that base, we have added a number of features and capabilities that enable simulation of the air-sea interface (e.g., surface waves) and other effects important for naval vessels. NavyFOAM is a fully parallelized, multi-physics computational fluid dynamics (CFD) framework developed using modern object-oriented programming (OOP). The code enables high-fidelity hydrodynamic analysis and prediction of ship performance such as resistance, propulsion, maneuvering, seakeeping and seaway loads. It has demonstrated accuracy against experimental data for a number of target applications such as resistance, propeller characteristics, hull/propulsor interaction, and six-degree-of-freedom ship motion of underwater vehicles and surface ships. Offering a suite of Navier-Stokes–based flow solvers tailored to specific applications including single- and multi-phase solvers, NavyFOAM allows assessment of alternative hull and propulsor designs. With NavyFOAM users can evaluate a ship's performance in a wide array of operating conditions and sea-states including both subsea and surface operations. Its modularity and software architecture expedites coupling with third-party software and collaborative multi-disciplinary software development (e.g., fluid-structure interaction, hydroacoustics). It has been applied to many naval systems including assessment of the safe operating envelope of the DDG-1000, propeller designs, the USMC Amphibious Combat Vehicle, the Columbia Ballistic Missile Submarine Program (a $100 billion procurement to replace the aging Ohio-class ballistic missile submarines) and many other systems of interest to the U.S. Navy.

IHDE—Integrated Hydrodynamic Design Environment (Facilitates Hydrodynamic Performance Evaluations for Early Stage Ship Design)

IHDE is a desktop application that integrates a suite of Navy hullform design and analysis tools allowing a user to perform evaluations of performance, including visualization, in a simplified and timely manner from a single interface. Prior to the development of IHDE, naval architects and marine engineers often had to learn how to use a dozen or more individual design tools, each with a different user interface and input format. IHDE provides a single interface for access to all of the tools. In a few days to weeks, a single user with IHDE can finish projects that used to take several highly experienced users many months to complete. Current capabilities are geared toward surface ships, both monohulls and multihulls—including catamarans and trimarans. Typical uses include predicting (1) resistance in calm water, (2) seakeeping behavior in waves, (3) hydrodynamic loads due to wave slamming, and (4) operability (percentage of time a ship can carry out its particular mission in various parts of the world based on historic sea state data).

The U.S. Navy's Center for Innovation in Ship Design (CISD) has used IHDE to assess the performance of many ship designs, including (1) T-AGOS-19 Ocean Surveillance ship; (2) Hospital ship (Mercy) replacement design; (3) Salvage Tow & Rescue (T-STAR); (4) Green Arctic Patrol Vessel (GPAV); (5) Medium Affordable Surface Combatant (MASC); and (6) an optimized MASC. IHDE is also an important adjunct capability for medium fidelity analysis of ship designs developed with RSDE. It was used with RSDE as part of the Amphibious Landing Craft LX(R) Analysis of Alternatives and the Small Surface Combatant Trade study. Its use with high performance computers will allow engineers to rapidly assess the major performance parameters of thousands to hundreds of thousands of candidate design options.

SENTRi—Electromagnetic Tools for DoD Systems

SENTRi is a robust and high-fidelity Full Wave electromagnetic prediction code for Radio Frequency (RF) modeling of antennas, microwave circuits, and radar cross-section prediction. SENTRi is designed for the modeling of complex structures—including highly heterogeneous material structures with multi-scaled features. A key goal is the calculation of the simultaneous performance of multiple-antenna systems embedded on a platform. The key features for electromagnetics are based on solutions of Maxwell's equations with advanced hybrid finite-element boundary-integral techniques. This provides high accuracy with the ability to solve large, complex problems. SENTRi is continuously validated with DoD measurements. SENTRi is being used for antenna design, antenna in-situ analysis, RF signature prediction, Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC), material modeling, microwave device analysis (i.e., waveguides, filters, circulators, power dividers), phased array antenna systems, and apertures (i.e., radomes, windows, frequency selective surfaces). SENTRi is being used by approximately 60 DoD organizations (government and industry).

CREATE Ground Vehicles (GV)

Mercury—Modeling and Simulation of Terrain Mechanics and Ground Vehicle Systems

Mercury incorporates suspension, tire and track, soil modeling, and powertrain simulation, and also integrates physics domains for powertrains, vehicle dynamics (wheels and tracks), and tire-soil and track-soil interaction. It simulates multiple performance tests used in vehicle acquisition: driver comfort (Ride/Shock), soft soil mobility (VCI1, sand-slope), maximum speed, vehicle stability (lane changes, circular turns). Mercury allows thousands of design concepts where the user can vary spring and damper properties, vehicle mass and inertia, tire properties, and axle spacing and location to be tested in a single simulation and provides performance metrics.

MAT—Mobility Analysis Tool

MAT is a computational tool for analyzing HPC physics data and producing mobility performance metrics required for trade exploration and systems engineering. It incorporates soil condition, vehicle performance and configuration, vegetation density, average surface roughness, average slope, and so forth. MAT converts physics-based vehicle performance data and terrain information into mission-based analysis of performance over large areas of terrain to predict percent GO/NOGO across selected terrains of interest and mission rating speeds. MAT interfaces with Mercury to use simulated performance data to provide performance metrics for concept designs.

Capstone—Rapid Geometry and Mesh generation

Capstone is a CAD-neutral application that provides two distinct capabilities. The first is the capability to develop numerical representations of a DoD weapon system (i.e., a Nonuniform Rational B-Splines [NURBS]–based digital product model consisting of the platform geometry with the associated attributes). The second is the capability to generate a mesh from the geometry. Valid and easily produced meshes with the required accuracy are the essential starting point for the other CREATE (solver) tools for detailed analysis. In addition, a number of non-CREATE groups use Capstone for its geometry and mesh generation capability for their applications.

A digital product model has many advantages for acquisition. It enables automated design optimization. It facilitates the transfer of design information between the government and contractors, eliminating much of the reliance on paper documents, and improving the accuracy and speed of information flow. It provides a permanent, analysable description of the platform through all stages of the acquisition process. Copies of the product model can be generated and assigned to individual airplanes and other systems allowing the DoD to track the history, performance and maintenance of entire life cycle of each individual platform. Together with DaVinci, which builds on top of the Capstone platform, it enables the recent Air Force initiatives of the Digital Thread and the Digital Twin (Kraft, 2015).

CREATE Program Organization and Management

To develop and deploy the CREATE software applications, we worked with the DoD organizations responsible for overseeing the design and analysis of air vehicles, naval vessels, RF antennas, and ground vehicles (Figure 2) to empower them to develop and deploy the tools. The CREATE Program first formed five projects with a total of 11 multi-disciplinary teams of DoD subject matter experts. Then we jointly identified a team leader within a DoD customer organization for each software product who possessed the right mix of subject matter and high performance computing expertise, and the required leadership, program, and project management skills. Then we helped the leader build a multidisciplinary software development team with approximately 10–15 members. Each core development group is located within a customer organization (e.g., the Navy's ship design groups are located at the Naval Surface Warfare Center, Carderock Division, Bethesda, MD, so the CREATE Ships team members are also Carderock employees and contractors and located there). Additional developers are drawn from other organizations as needed to provide required expertise not available in the customer organization. For instance, the structural dynamics modules for NESM and Kestrel are being supplied by the Sierra Mechanics group at the U.S. Department of Energy's (DOE's) Sandia National Laboratory as part of a highly productive DOE/DoD inter-agency collaboration. Generally about one third of each team resides at the core organization, and the remaining two-thirds are located at other organizations. The CREATE staffing mix is about 90 DoD employees and about 90 DoD support contractors. The team members are distributed across ~30 collaborating organizations.

Embedding the code teams and the team leaders in the relevant DoD customer organization greatly improves our ability to recruit the most capable talent in the DoD for each technical area. It also helps ensure adoption and ownership of the CREATE tools by the relevant Service since their experts are responsible for developing the tools and are "trusted agents" of that Service. In many cases the design engineers for the relevant weapon systems are collocated with CREATE tool developers. This helps the developers get rapid feedback on the usability and accuracy of the code, and a sense of satisfaction from directly seeing the impact that the code is having on the DoD.

The CREATE Program leaders sponsor each team by providing funding and active management and oversight of the code development process. We developed a set of software project management and software engineering practices for the CREATE Program and promulgated them to the teams as guidance. We sought a balance between a very agile code development process to allow the code development teams the flexibility to accomplish technically difficult tasks while ensuring adequate accountability together with an organized code development process. The HPCMP and CREATE Program Office actively manages the 11 teams cooperatively with the hosting Service organizations. While clear lines of authority and obligation have been formally established between the HPCMP CREATE program and each executing and hosting organization, both groups have developed a high degree of trust and work together to resolve conflicts. There is a strong degree of alignment on the technical aspects of the CREATE Program between the CREATE Program leadership and the Service organizations.

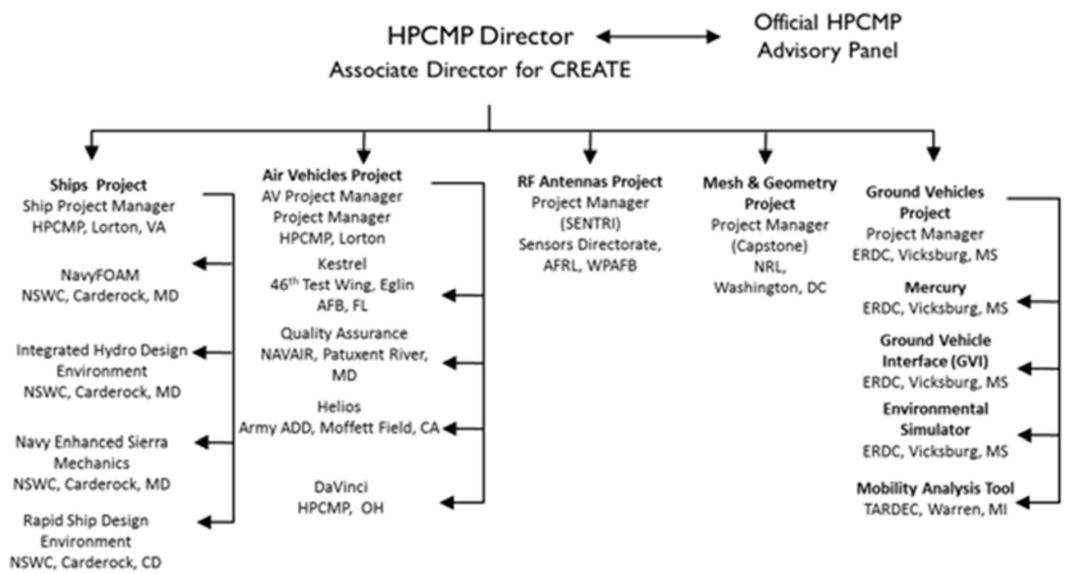

Figure 2. CREATE Program Organization Chart

Each project has a board of directors consisting of senior members of the relevant customer organization (Navy, Air Force, and Army acquisition engineering communities). Each board meets at least once a year. The boards review the progress during the prior year, advise the project about new requirements, and serve as liaisons between the CREATE projects and their DoD customer community. The board members are members of the Senior Executive Service, or other senior staff of the Navy, Air Force, or Army. The boards provide an additional mechanism for ensuring that the CREATE tools are aligned with the needs of the Services.

The annual CREATE budget is about $30 million/year. The total investment in CREATE by the DoD HPCMP from 2008 through 2015 is ~$200 million. The Services provide "in-kind" contributions of another ~$11 million/year, a testament to the value of CREATE to them. The Service contributions include office space and supplies, administrative support, network and other host services, additional professional staff for the code development teams, and access to validation experiments and data.

Building the Right Software Right

At the beginning of the CREATE Program, we developed a vision for how the DoD could implement virtual prototypes with physics-based high performance computing engineering software within its own processes to "modernize" its acquisition process. We then fleshed out that vision through joint assessments with each service of their detailed acquisition processes to identify the specific tools needed to reduce the time, cost, and risk and improve the system performance for the Service's acquisition programs. For instance, the CREATE Air Vehicles Program assessed 27 different acquisition workflows to develop its requirements. This vision is captured in an "Initial Capability Document" (ICD) for each project. The ICDs were reviewed and approved by the Board of Directors for each project and are reviewed periodically.

Although CREATE was proposed to be a 12-year program, the CREATE tools are designed for a 30 to 40-year life since that is the expected life span of successful engineering codes. Since the DoD spends roughly $200 billion/year acquiring, maintaining, sustaining, and modifying major weapon systems, the expectation has been that if the CREATE tools were successful in enabling the DoD to significantly improve acquisition outcomes for an expenditure of ~$30 million/year (0.00015 of $200 billion/year), the tools would be supported and continue to be modernized until they were no longer needed.

Fiscal Year	FY2011				FY2012				FY2013				FY2014				FY2015				FY2016				FY2017				FY2018 Planned				FY2019 Planned			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
AV-DaVinci					1							2								3				4				5				6				7
AV-Helios					2				3			4					5				6					7				8				9		
AV-Kestrel			2						3			4				5			6					7			8				9				10	
MG-CAPSTONE	1				2				3				4				5				6				7				8				9			
RF-SENTRi				2					3				4				5				6					7				8				9		
Ships-IHDE	2				3				4				5				6				7				8				9				10			
Ships-NavyFOAM	1				2				3					4			5				6				7				8				9			
Ships-NESM	1				1.1					2					2.1				3				4				5				6				7	
Ships-RSDE					0.5				1.0				1.1				1.2					2						3				4				5
GV-Mercury																												1				2				3

Figure 3. CREATE Annual Releases With Version Numbers

Note. The FY2017 3rd quarter and subsequent releases are planned. Some CREATE products had releases prior to 2011.

Each CREATE code development team follows a highly disciplined software development process. There is a strong emphasis on software quality. To facilitate development by non-collocated teams, the CREATE Program, through the DoD HPCMP, provides a supportive code development environment with virtual clusters, central servers with code and document repositories, issue trackers, user and developer forums, configuration management services, and access to high performance computers for testing and performance enhancement, and high quality video conferencing. Guided by the ICD, a 12-year product roadmap and feedback from the BODs and customers, each product team issues a new release each year with the upgraded capability and new features needed by the customer communities. This places the upgraded tool into the hands of the user community and gives the code development team rapid feedback on the quality and usefulness of the upgraded code. The annual release cadence (Figure 3) adds discipline and accountability to the development process and is a key factor in the success of the CREATE development process.

The CREATE teams generally use an "agile" development process tailored for their environment and code. The releases are designed and tested for all the standard Linux and Unix HPC operating systems, as well as MacOS and Windows where appropriate. Each release is extensively tested both during the development process, and as an integral part of the release process. Each software release is documented with a (1)Product Technical Description that describes the physics and engineering capabilities (including the equations) in the code, the computer science approaches, software architecture, and solution algorithms; (2) Developers Manual that describes the source code in detail, provides an index/table of contents, and other information essential for understanding the source code; (3) Users' Manual to help the users set up their problems, run the code, and analyze the results; and (4) Test Plan with an archive of test problems with the input and test results. In addition, there are tutorials and a user forum on the CREATE server, all backed up by a user support group.

Information Assurance for the CREATE Products

Information assurance for computational engineering applications can be understood from its role in the high performance computing (HPC) ecosystem. The CREATE tools are part of an ecosystem consisting of (1) Subject Matter Experts (SMEs) who use the tools on high performance computers over high speed networks to generate virtual prototypes and analyze their performance; (2) software applications like the CREATE tools that can be used to generate virtual prototypes and predict their performance; (3) Experimental testing organizations to generate validation data to establish the validity of the models that are the basis of the software applications; (4) high speed computer networks that provide the SMEs access to supercomputers; (5) supercomputers; and (6) sponsors who need the results of the calculations and provide the funds to generate the results.

CREATE is designed to provide the DoD with a military competitive advantage. Thus the CREATE Program and the DoD must control the distribution and use of the codes to sustain that advantage. The CREATE codes are unclassified but are subject to the International Traffic in Arms Regulations (ITAR). To be effective, DoD users must be able to run the CREATE codes securely and access their proprietary data on a high performance computer. The codes and data are encrypted at rest and accessed and transferred over a secure encrypted network with two-factor authentication. To ensure integrity of the codes and the users' data, the codes and the user's data are archived on the secure HPCMP supercomputers and backed up frequently to several remote secure data repositories.

However, many, if not most, DoD users (engineers) have access only to a Windows Personal Computer (PC) with Microsoft Office and a browser. Usually no other software is allowed on these PCs so those engineers cannot easily access the HPCMP supercomputers and the CREATE tools. To remove this barrier to access, the DoD HPCMP and the CREATE program have developed a "portal" that allows DoD users to access the DoD HPCMP supercomputers through their browser. The "portal" features two-factor authentication and encrypted data transfer. It allows users to securely set up their job; run it; and store, analyze, and visualize the results through their browser.

To prevent unauthorized access to the CREATE codes and to the intellectual property of the users, we limit access to codes to DoD employees or DoD contractors who have a valid reason for access to the CREATE software. They must sign a software distribution agreement that describes the limitations of their use (not to redistribute the code, reverse engineer it, etc.) and their intended use. They also agree to abide by the ITAR procedures which have civil and criminal penalties if violated. The CREATE source code is only accessible to the development team. The ideal is a "Software as a Service" model where the user can only execute the code, but not get a copy, even an executable. However, that's not practical for some users, and those users are handled on a case-by-case basis.

Intellectual Property Rights

The DoD HPCMP must have "government purpose rights" to be able to distribute the CREATE software to users. Even a single line of code for which the DoD doesn't have these rights would leave the DoD vulnerable to lawsuits and large financial settlements for copyright or patent infringement and theft of intellectual property. Legal reviews of the ~40 CREATE support contracts have determined that the DoD does have "government purpose rights." Remedial action was necessary for some of the contracts.

It is DoD policy to share DoD RDT&E results with the U.S. defense industry if it is in the interests of the DoD because a strong U.S. defense industry is essential for national security (Weiss, 2014). Several defense industries have expressed a strong interest in adopting the CREATE tools for use in their commercial as well as military design work. This requires that the DoD have "unrestricted rights" for the relevant CREATE software. As the result of further extensive legal reviews of the CREATE AV contracts over the last three years, together with additional remedial action, the DoD now has "unrestricted rights" to the CREATE AV tools. We anticipate that several large defense companies will be using CREATE AV tools for both military and commercial systems, and a few key defense industries have already expressed interest in this type of use.

Transition and Adoption

Transition of research results to applications and products has been a historic challenge for much of the science and technology research done by the DoD research community. The approach adopted by the CREATE Program of embedding the CREATE development teams in the DoD customer organizations responsible for the design and development of the relevant weapon system has been very successful in overcoming that challenge. The CREATE teams are trusted agents of their DoD organization. For example, to assess various options for a follow-on to the Littoral Combat Ship, or to develop a concept for the Ohio replacement submarine, the Navy turned to the trusted organizations responsible for those tasks, the Naval Architecture and Engineering Department at the Naval Surface Warfare Center at Carderock. These were the same groups developing the ship design tool, RSDE and the hydrodynamics tool NavyFOAM. The transition was almost automatic.

In general, computational design tools are very effective methods for capturing the corporate knowledge and new research results in a field, and giving design engineers access to that knowledge in a tool that the engineer can use to design a new system. This greatly facilitates the development of innovative designs. It also gives a design engineer the opportunity to compare the impact of new research results in the context of present practice, and allows the engineer to answer many "What if?" questions and define the benefit of the research for the system of interest. It facilitates a successful transition from research to practice, a transition across the "Valley of Death." This has been recognized by a number of groups in the DoD science and technology research community. Some of those groups are beginning to work with the CREATE team to incorporate their research results into the CREATE codes as a means to transition their research results to acquisition programs. For instance, the CREATE Kestrel group is working with the DoD hypersonics R&D community to develop a version of Kestrel that incorporates the most recent research results on the behaviour of hypersonic air platforms. Aerospace engineers are familiar with Kestrel as a validated, user-friendly multi-physics aerospace engineering tool for sub-sonic, transition, and super-sonic flight conditions. In a few years, they will have access to the same mature engineering tool that has been upgraded to handle supersonic flight.

Accelerating the Development of Innovative Weapon Systems With Virtual Prototyping and HPC

The CREATE tools enhance the ability of DoD engineers to develop innovative weapon systems. With the CREATE tools, these engineers can develop thousands, even hundreds of thousands of design options for potential weapon systems, capture their properties in digital prototypes, assess the feasibility and capability of each prototype with physics-based tools, perform trade-space studies of the prototypes, and develop optimized designs. Then high-fidelity tools such as Kestrel and NavyFOAM can be used to assess the performance of the final selected design option, a "virtual test." This process can be done in weeks to months for hundreds of thousands of design options, much faster than is the case with physical prototypes that are currently proving to take tens of years to design, develop, and test prototypes for only a few candidate design options. This allows the rapid identification of design defects and performance shortfalls, well before metal is cut. In addition, changes in requirements can be inserted into the design process at almost any point until very late in the design process.

History convincingly illustrates that continual innovation in military technology is necessary for achieving and sustaining the competitive military technological advantage needed for national survival (Colinvaux, 1980; Kennedy, 1987). By most accounts, the worldwide rate of technological change will remain high, or even increase (Desilver, 2014). In this context, the United States would benefit from a faster and more agile major weapon development process. DoD leadership has recognized this and launched an effort to tap the innovation skills of Silicon Valley (the Defense Innovation Unit Experimental; see https://www.diux.mil) for DoD acquisition. Virtual prototypes and high performance computing offer the DoD an additional opportunity to apply a number of the features of the innovation culture of Silicon Valley (Table 2) identified in several short papers published by the *Harvard Business Review* (Anthony, 2013; Fox, 2014; Martins, Dias, & Khanna, 2016) to accelerate innovation in the acquisition of major DoD weapon systems.

Innovation requires the right people working in the right environment and with the right tools. In Silicon Valley the product development teams at successful companies are small, able to take risks, rapidly develop and try many new product features, and go through many trials and failures until success is achieved. The development and design teams own the development process. They have the autonomy to be resourceful and make decisions. They are able to learn from failures and adapt as the product design evolves. They have a day-to-day determination to see something through despite near-constant failure. The corporate environment is generally flat. Corporate management is accessible to the teams for advice, support, and requests for resources. All the expertise in the company is accessible to the teams. There is continuity in the corporate leadership, leading to continuity in the corporate memory.

Table 2. Some Key Features of Silicon Valley Innovation Culture

- Small teams with significant autonomy that are empowered to take risks and make decisions
- Generally flat organizations, but with a clear hierarchy
- Early development and testing of many options and alternatives
- Early identification of things that work and those that do not
- Fanatical pursuit of promising options to a successful conclusion
- Leadership continuity
- Close working relations and connections with customer communities
- Emphasis on incremental improvements and modifications, as opposed to huge leaps
- Silicon Valley mostly focused on information technology with small sized products (smartphones, integrated circuits, music players, computers, calculators, etc.), but—
    - New aerospace and automotive start-ups such as Space-X, Blue Origin, Virgin Galactic, Facebook Aquila, Tesla, Google Car, etc. with industrial scale products retain many of their Silicon Valley roots and features.

The best teams are typically small and almost fanatically focused on producing features that attract users and customers. The team members work collaboratively with each other with a minimum of structure and formality. They move around the company and the industry, learning new skills and encountering new ideas. Organizations and companies are fairly flat, not rigidly hierarchal. Management typically sets goals and enforces accountability, but the teams have the agility and flexibility to develop the product. Rigid planning is not conducive to inventing something new. This is not what one finds in large aerospace industries or the DoD, even if the operational part of the DoD does share many of these features (Reinertsen, 2009).

Another feature common in Silicon Valley is that successful innovation is often more an evolutionary improvement than a discontinuous and revolutionary advance over present capabilities. New products in Silicon Valley are often incremental improvements of yesterday's products. Today's iPhone7 is the 20th generational descendant of the Apple Newton introduced in 1993 (Table 3). In contrast, many large defense acquisition projects are structured to produce products that embody very large advances over the capabilities of existing systems with few or no intermediate steps. While the F-22 was a major step forward in terms of stealth, it took 19 years from the start of the project to the delivery of the first operational F-22. During the 26 years of the F-22 program, the Soviets/Russians fielded six generations of surface-to-air missiles. In contrast, innovation in Silicon Valley is usually the result of many failures that lead to a series of small successes and small evolutionary advances (e.g., iPhone 5 to iPhone 6), ending up in revolutionary advances in capability (i.e., Newton to the iPhone 7 over the course of 23 years).

Table 3. History of the iPhone

("History of the iPhone," n.d.)

1993	Newton
1994	120
1998	Apple Message Pad 2100
2005	ROKR
2006	
2007	iPhone (1st generation)
2008	iPhone 3G
2009	iPhone 3GS
2010	iPhone 4
2011	iPhone 4S
2012	iPhone 5
2013	iPhone 5S iPhone 5C
2014	iPhone 6/6+
2015	iPhone 6S/6S Plus
2016	iPhone SE iPhone 7/7 Plus

This incremental approach may not appear to be immediately applicable to the latter stages of the development of large-scale weapon systems, particularly aircraft carriers, submarines, large surface ships, or many other complex weapon systems. It now takes at least 10 to 15 years to design and build a nuclear aircraft carrier for ~$13 billion or more. The cost and national importance of this type of system provides considerable incentives to minimize risk, so innovations must be and are introduced cautiously. The infrastructure to build large systems also takes time to construct, either by modification of existing facilities or construction of new ones. However, as noted above, many aerospace and automotive start-ups that can trace their roots to Silicon Valley start-ups (e.g., Space-X), are building large-scale, complex systems, and are certainly among the most innovative members of their industry. Many strongly emphasize the use of computational prototypes with high performance computing. The advantages of computational prototyping are still very applicable to the early stages of design concept development and detailed engineering design. Also, even though most IT products are small in physical size compared to ships and airplanes, the infrastructure required to build them, such as chip fabrication facilities, can cost many billions of dollars. Finally, the integrated circuit vendors (e.g., INTEL) rely strongly on computational prototyping. They construct a computational prototype for every new chip. It is the only way they can design the layout and test it to put billions of components on a single chip successfully (Colwell, 2005).

Summary and Future

The CREATE Program is successfully developing and deploying a suite of physics-based computational engineering software tools with the design and analysis capabilities needed by the DoD Air Vehicle, Ship, RF, and Ground Vehicle acquisition engineering communities to reduce the cost, schedule, and risk of acquisition programs. The CREATE tools enable DoD engineers to generate and analyze virtual prototypes of DoD Air Vehicles, Ships, RF antennas and, in the future, Ground Vehicles, and to accurately predict the performance of the weapon systems. This approach to product development accelerates the development of innovative systems because it enables design engineers to rapidly develop, analyze, assess, optimize, and test many design options, without having to construct and test physical prototypes until late in the product development process. Design defects and performance shortfalls can be detected and fixed well before metal has been cut.

At the latest count, over 160 DoD acquisition engineering organizations (government, industry, and academia) are using the tools to design and assess over 70 DoD weapon systems. Acquisition community interest and customer use is growing exponentially (AF, Navy & Army engineers, Boeing, LMC, NG, Raytheon, Sikorsky, Bell, Pratt & Whitney, AFLCMC, AMRDEC, NAVAIR, NAVSEA, C-130/C-17 Cargo Release, F/A-18E, ARL, SPAWAR, Ball Aerospace, etc.). The CREATE tools are already enabling the design and analysis of many important DoD systems (e.g., CH-47 rotor-blade retrofit, Ohio replacement submarine, CVN-78 shock test, NAVAIR UAV flight certification, Air Force next-generation aircraft). The CREATE Program has made significant progress to successfully overcome major challenges to provide user support, resolve intellectual property issues, achieve successful deployment of software, and implement sound software engineering and software project management practices that lead to a high level of software quality, software that is usable, maintainable, verified and validated, extensible, scalable, and documented.

After 10 years of development and deployment, the CREATE Program is beginning to achieve the goal of revolutionizing the way the DoD procures major weapon platforms through the use of virtual prototypes. These tools will enable the DoD acquisition engineering community to develop innovative weapon systems by allowing DoD engineers to generate and evaluate thousands of design options, rather than the handful that was previously possible.

The CREATE tools are government-developed, government-owned, and government-supported so that the DoD can independently evaluate contractor deliverables. The tools are designed to be sufficiently robust and useable that experienced engineers with good judgment can utilize the tools with confidence. The tools are designed and built for a

~30-year plus life cycle. The tools are on the verge of being adopted by the defense industry for commercial use, so that they will contribute to a strong U.S. economy, as well as to a strong U.S. defense. The tools are also beginning to be used to improve the effectiveness and efficiency of DoD T&E enterprises.

By 2019, each CREATE tool will deliver the capability promised in its 12-year vision. That capability, however, offers a foundation to fill many other DoD capability gaps and is an important part of the HPCMP mission for continuous modernization of hardware (DSRCs), networks (DREN), and defense-specific software applications. The CREATE tools are foundational elements of the OSD Engineered Resilient Systems S&T Initiative (Goerger, Madni, & Eslinger, 2014) and the Air Force Digital Thread and Digital Twin Programs (Kraft, 2015).

The CREATE team is proposing enhancements and upgrades to the existing CREATE that would greatly increase their range of applicability and impact. These include upgrades to Kestrel to address hypersonic design tasks, an addition of the ability of RSDE and DaVinci to estimate life cycle cost, the ability to produce a full conceptual ship design including integrated compartment arrangements and hullform optimization, operational assessments, and other aspects of multi-hull surface ships and submarines. With additional funding it would be possible to start new CREATE projects to address DoD capability gaps such as prediction and design of space satellite performance, rocket propulsions systems, structural performance design, combat power and electrical systems layout, and electronic warfare systems. The CREATE development process has proved very successful, and points the way for the DoD to develop tools to generate virtual prototypes of many different DoD systems and to predict their performance with physics-based computational tools.

References

Anthony, S. (2013, July 30). Five ways to innovate faster. *Harvard Business Review*, 3.

Ball, D. (2009). *Boeing catches a lift with high performance computing*. Paper presented at the Council on Competitiveness, HPC Success Stories.

Carter, A. (2013). *Defense acquisition* (DoD Instruction 5000.02). Retrieved from http://www.acq.osd.mil/fo/docs/DSD%205000.02_Memo+Doc.pdf

Colinvaux, P. (1980). *The fates of nations: A biological theory of history*. New York, NY: Simon and Schuster.

Council on Competitiveness. (2010). *Council on Competitiveness: HPC success stories.* Retrieved from http://www.compete.org/about-us/initiatives/hpc/success%20stories

Desilver, D. (2014). Chart of the week: The ever-accelerating rate of technology adoption. Retrieved from http://www.pewresearch.org/fact-tank/2014/03/14/chart-of-the-week-the-ever-accelerating-rate-of-technology-adoption/

Colwell, R. P. (2005) *The Pentium Chronicles: The people, passion, and politics behind Intel's landmark chips.* Wiley-IEEE Computer Society.

Engardio, P. (2008, September 20). Chawla, S.K. Los Alamos and Sandia: R&D treasures by S.K. Chawla. *Businessweek Magazine.*

Fox, J. (2014, December 5). What still makes Silicon Valley so special. *Harvard Business Review.*

Francis, S. (1995). *Warhead politics, Livermore and the competitive system of nuclear weapon design* (UCRL-LR-124754).

Goerger, S. R., Madni, A. M., & Eslinger, O. J. (2014). *Engineered resilient systems: A DoD perspective*. Paper presented at the 2014 Conference on Systems Engineering Research.

History of the iPhone. (n.d.). In *Wikipedia*. Retrieved from https://en.wikipedia.org/wiki/History_of_iPhone)

Keagan, R. J. (2010). *The road before us: 2009 Goodyear Annual Report.*

Kennedy, P. (1987). *The rise and fall of the great powers: Economic change and military conflict from 1500 to 2000*. New York, NY: Random House.

Kossiakoff, A., & Sweet, W. (2003). *Systems engineering principles and practice*. Hoboken, NJ: John Wiley and Sons.

Kraft, E. M. (2010, September). After 40 years why hasn't the computer replaced the wind tunnel. The *ITEA Journal of Test and Evaluation, 31*, 329–346.

Kraft, E. M. (2015). *HPCMP CREATE^TM-AV and the Air Force digital thread.* Paper presented at the Proceedings of the 53rd AIAA Aerospace Sciences Meeting, AIAA 2015-0042, Kissimmee, FL.

Kramer, R. J. (2011). *Goodyear Tire & Rubber Q4 2010 earnings call*. Retrieved from http://www.nasdaq.com/aspx/call-transcript.aspx?StoryID=252155&Title=goodyear-tire-rubber-s-ceo-discusses-q4-2010-results-earnings-call-transcript

Martins, H., Dias, Y. B., & Khanna, S. (2016, April 26). What makes some Silicon Valley companies so successful. *Harvard Business Review*.

Miller, L. K. (2010). Simulation-based engineering for industrial competitive advantage. *Computing in Science and Engineering, 12*(3), 14–21.

Post, D., Atwood, C., Newmeyer, K., Meakin, R., Hurwitz, M., et al. (2016). CREATE: Software engineering applications for the design and analysis of air vehicles, naval vessels, and radio frequency antennas. *Computing in Science and Engineering, 11*, 14–24.

Reinertsen, D. (2009). *The principles of product development flow*. Redondo Beach, CA: Celeritas.

Singer, D., Doerry, N., & Buckley, M. (2009). What is set based design? *Naval Engineers Journal, 121*(4), 31–43.

Walser, A. F. (2014). *Drive safe, green and smart: HPC applications for sustainable mobility.* Paper presented at the When Science Meets Industry PRACE Scientific and Industrial Conference. Retrieved from http://www.prace-ri.eu/IMG/pdf/pracedays14_walser.pdf

Weiss, L (2014). *America, Inc.: Innovation and enterprise in the national security state*. Ithaca, NY: Cornell University Press.

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