Engineered Resilient Systems (ERS) S&T Priority Description and Roadmap

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Resilient Systems, Defined

A resilient system is trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function.

DoD S&T Focus Areas

SECDEF Guidance

SECRETARY OF DEFENSE
1000 DEFENSE PENTAGON
WASHINGTON, DC 20301-1000

APR 19

MEMORANDUM FOR SECRETARIES OF THE MILITARY DEPARTMENTS
CHAIRMAN OF THE JOINT CHIEFS OF STAFF
UNDER SECRETARY OF DEFENSE FOR ACQUISITION, TECHNOLOGY AND LOGISTICS
ASSISTANT SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING
DIRECTORS OF THE DEFENSE AGENCIES

SUBJECT: Science and Technology (S&T) Priorities for Fiscal Years 2013-17 Planning

The Department's S&T leadership, led by the Assistant Secretary of Defense for Research and Engineering, in close coordination with leadership from the Under Secretary of Defense for Policy, the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense, the Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base Policy, and the Joint Staff, has identified seven strategic investment priorities. These S&T priorities derive from a comprehensive analysis of recommendations resulting from the Quadrennial Defense Review mission architecture studies directed in the FY12-16 Defense Planning Programming Guidance.

The priority S&T investment areas in the FY13-17 Program Objective Memorandum are:

(1) **Data to Decisions** – science and applications to reduce the cycle time and manpower requirements for analysis and use of large data sets.
(2) **Engineered Resilient Systems** – engineering concepts, science, and design tools to protect against malicious compromise of weapon systems and to develop agile manufacturing for trusted and assured defense systems.
(3) **Cyber Science and Technology** – science and technology for efficient, effective cyber capabilities across the spectrum of joint operations.
(4) **Electronic Warfare / Electronic Protection** – new concepts and technology to protect systems and extend capabilities across the electro-magnetic spectrum.
(5) **Counter Weapons of Mass Destruction (WMD)** – advances in DoD's ability to locate, secure, monitor, tag, track, interdict, eliminate and attribute WMD weapons and materials.
(6) **Autonomy** – science and technology to achieve autonomous systems that reliably and safely accomplish complex tasks, in all environments.
(7) **Human Systems** – science and technology to enhance human-machine interfaces to increase productivity and effectiveness across a broad range of missions.

OSD 02073-11

19 April 2011

Complex Threats

Electronic Warfare / Electronic Protection

Cyber Science and Technology

Counter Weapons of Mass Destruction

Force Multipliers

Autonomy

Data-to-Decisions

Human Systems

Engineered Resilient Systems

Engineered Resilient Systems (ERS): A DoD Perspective

"...our record of predicting where we will use military force since Vietnam is perfect. We have never once gotten it right.

There isn't a single instance ... where we knew and planned for such a conflict six months in advance, or knew that we would be involved as early as six months ahead of time.

… we need to have in mind the greatest possible flexibility and versatility for the broadest range of conflict..."

The Honorable Dr. Robert M. Gates
22nd Secretary of Defense
24 May 2011

Deputy Secretary of Defense Ashton Carter is charged with, "...eliminating wasteful spending, consolidating duplicative functions, and driving ongoing and new efficiencies initiatives that can help us achieve the aggressive budgetary goals we have set."

The Honorable Leon Panetta
23rd Secretary of Defense
6 Oct 2011

ERS: a DoD-wide science and technology priority

- Established to guide FY13-17 defense investments across DoD
- Ten year science and technology roadmap under development
- Five technology enablers identified

ERS Impact on Operational Capability

- **Transforming engineering practices to efficiently create, field and evolve trusted defense systems which can readily adapt to the inevitable changes in threat, technology, and mission environments**
- **Advancing productivity of US industrial base to develop and adapt defense systems within the rapid time cycle of technology and mission changes**
- **Improving DoD responsiveness to user needs by developing and deploying new concepts, tools and techniques for reliable delivery of defense systems**
- **Developing trusted systems from untrusted components**

Getting inside adversaries' innovation and adaption cycles

Problem Statement:
Need for Engineered <u>Resilient</u> Systems (ERS)

- **Wide span of missions, with increasing uncertainties and risks**
  - DoD must be prepared to support a very wide range of missions (from HA/DR to conflict with a near-peer state)
  - Rapid changes in missions, threats and operating environments create uncertainties in military requirements
  - Availability of global commercial technology poses an advantage for adversaries; dependence on global technology poses trustworthiness risks for DoD
- **Current engineering and business processes were designed for stable requirements and trusted suppliers**
  - Analyze fixed requirements and synthesize a point solution for delivery years later
  - Strong measures for assurance in only the most critical designs (e.g. nuclear)
- **New processes and tools are needed for <u>Resilient</u> Systems**
  - Compensate and recover from disruptions; adapt to dynamic environments and rapidly deliver new solutions

Change happens! Engineer for it…..

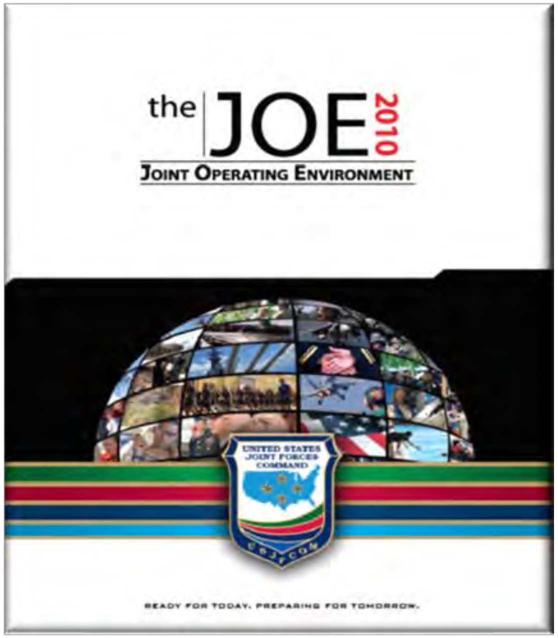
What's New

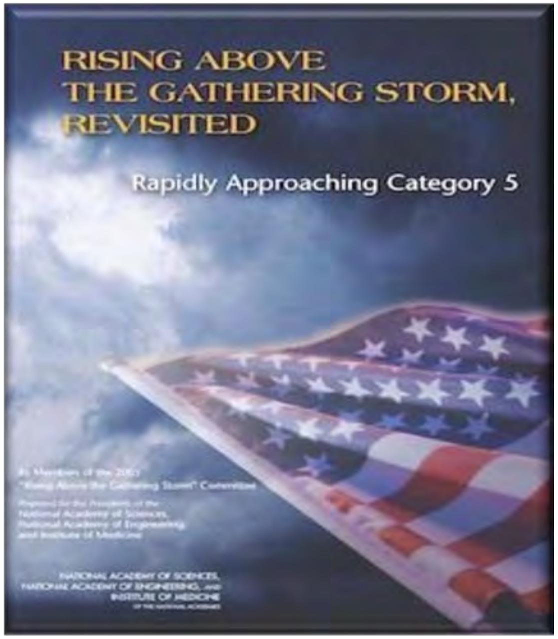
- **Focus on re-design: retrofit/upgrade/adapt more quickly and for less $$**
- **Rapidly vector in on feasible reconfigurations and extensions**
  - Without loss of confidence in security
- **Focus on design and testing in context**
- **Model more of the operating environment**
- **Explore and evaluate current and future scenarios, jointly with associated CONOPS**

Terminology

- **Model:** a specification of behavior and/or physical characteristics, expressed in a human- and machine- interpretable form, that supports both analysis and simulation
- **Platform:** the architecture, framework, or base set of physical elements that enables a family of related products to be produced through rapid reconfiguration of modules
- **Tradespaces**: the set of alternative products (product families) that offer acceptable combinations of values or attributes relative to some range of alternative futures
- **Alternative futures:** a range of contexts (environmental conditions, anticipated threats, and Concepts of Operation) for which a system design is either being requested or is being considered for application
- **Conceptual design:** Collaboratively creating a set of easily changed, closely linked requirements and architecture(s) that notionally describe the behavior and performance of a proposed system or SoS, with respect to a set of potential contexts.
- **Capability engineering**: Iterative refinements and tests (and, if necessary, revisiting of) a conceptual design to produce detailed CAD and manufacturing models
- **Resilience:** the ability of a family of products to serve effectively in multiple alternative futures, despite uncertaintainties about individual component performance, through rapid reconfiguration or replacement.

Global Shifts → Global Challenges





Shift in World Demographics

Technology Globalization

Shifting Global Economics

Limited World Energy Resources

Challenges to Existing State Structures

WMD proliferation

Innovation & Competitiveness

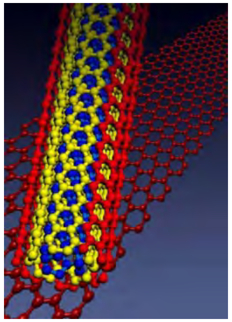
Knowledge Capital

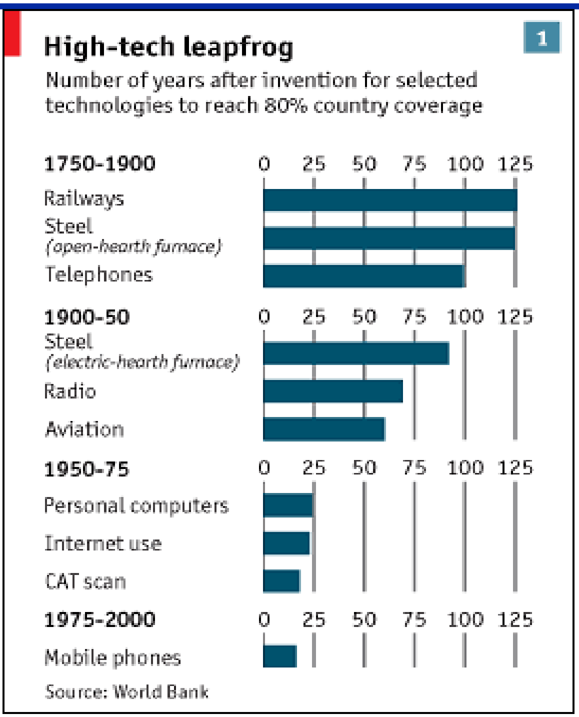
Human Capital

Creative "Ecosystem"

Pace of Technology Continues to Increase

- **Time between modeling of semiconducting properties of germanium in 1931 and first commercial product (transistor radio) was 23 years**
- **Carbon nanotube**
  - **Discovered by Japan (1991)**
  - **Researchers recognized carbon nanotubes were excellent sources of field-emitted electrons (1995)**
  - **"Jumbotron lamp" - nanotube-based light source available as commercial product (2000)**
- **Information Technology**





The Economist, Feb. 9, 2008

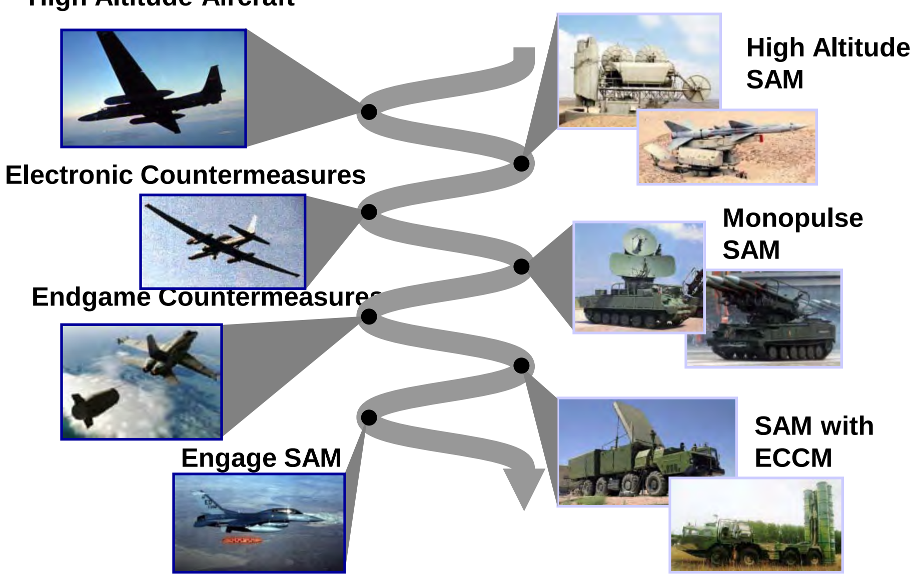
Cloud Computing

1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008

The Timeline has Collapsed (For Military Systems)!

Conventional Warfare

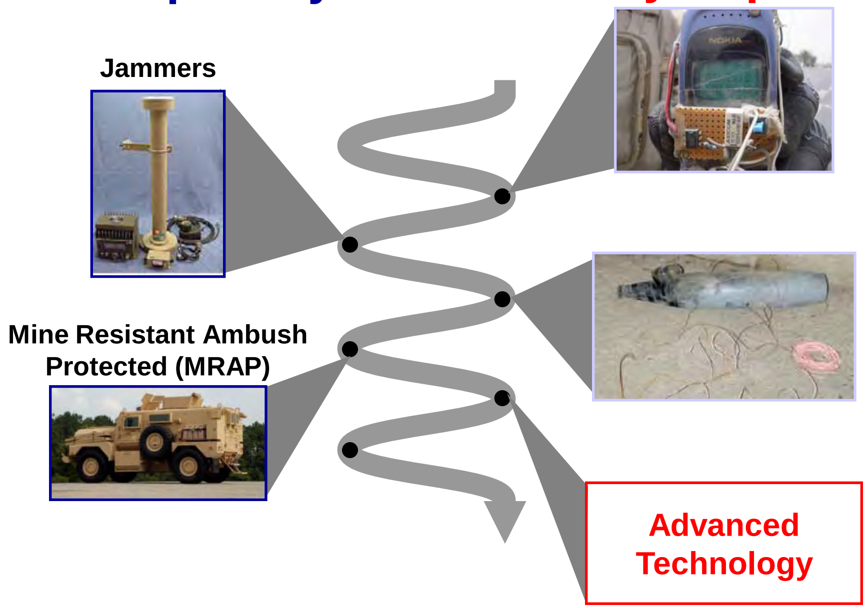
US Capability **Adversary Capability**



RESPONSE LOOP MEASURED IN YEARS OR DECADES

Counter-Insurgency Warfare

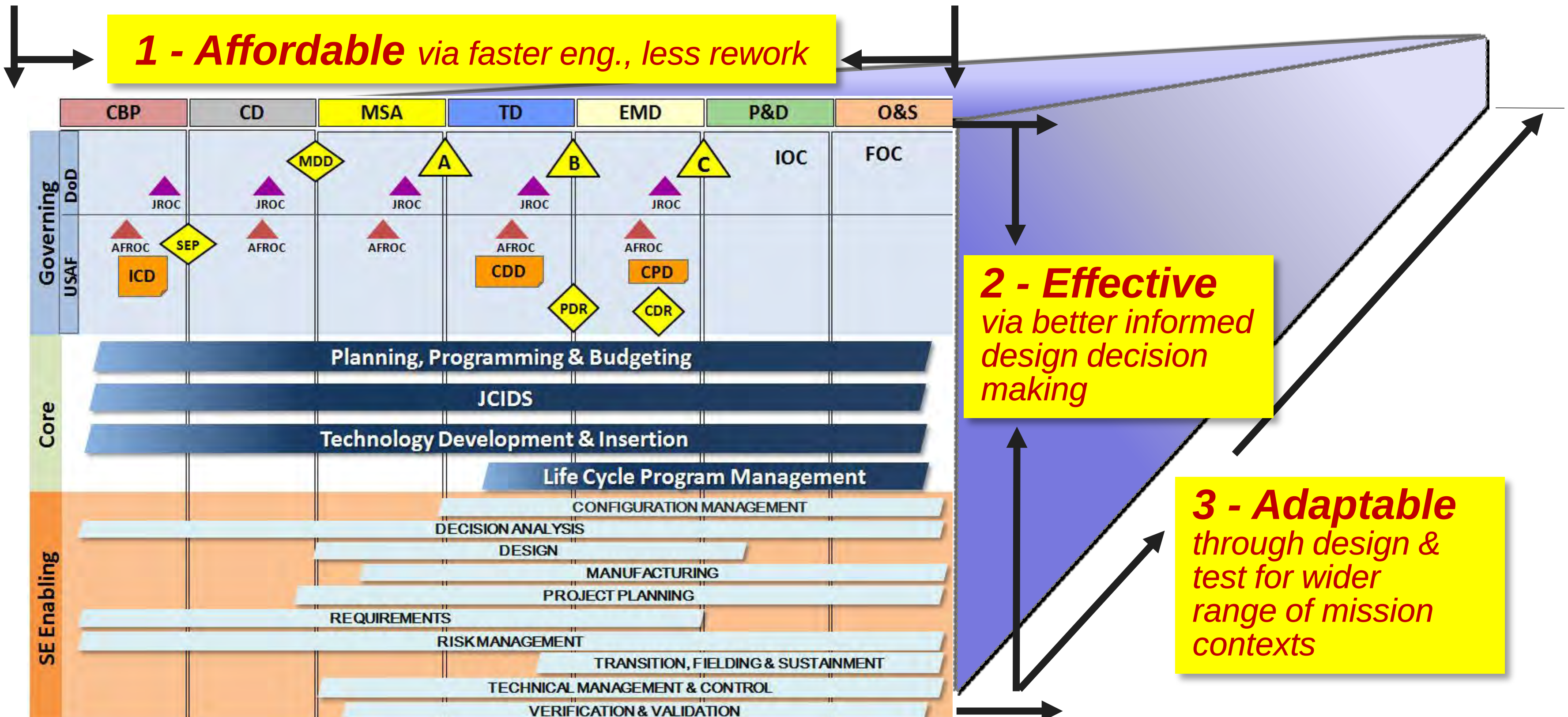
US Capability **Adversary Capability**



Response loop measured in *months or weeks*

Engineered Resilient Systems Spans the Systems Life cycle

Resilience: Effective in a wide range of situations, readily adaptable to others through reconfiguration or replacement, with graceful and detectable degradation of function



Uncertain futures, and resultant mission volatility, require affordably adaptable and effective systems – done quickly

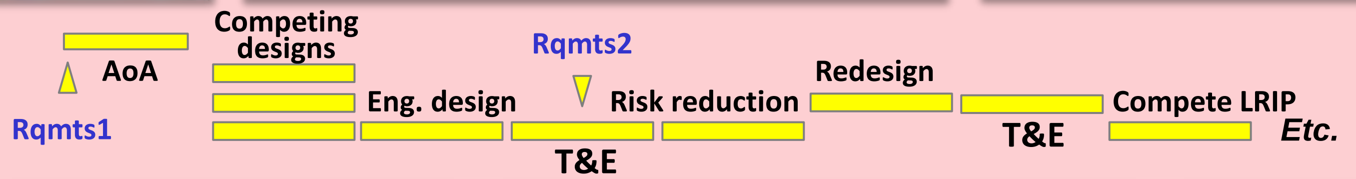
The Problem Goes Beyond Process:
Need New Technologies, Broader Community

Today

Prematurely reduces alternatives

Decisions made w/o info

50 years of process reforms haven't controlled time, cost and performance



Sequential and slow

Information lost at every step

Ad hoc reqmts refinement

The Future

Fast, easy, inexpensive up-front engineering:

- Automatically consider many variations
- Propagate changes, maintain constraints
- Introduce and evaluate many usage scenarios
- Explore technical & operational tradeoffs
- Iteratively refine requirements
- Adapt and build in adaptivity
- Learn and update

*New tools **help Engineers & Users** understand interactions, identify implications, manage consequences*

Engineered Resilient Systems: Needs and Technology Issues

Creating & fielding affordable, effective systems entails:

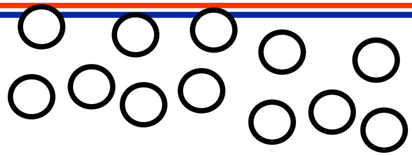
- **Deep trade-off analyses across mission contexts**
  - **Adaptability, effectiveness and affordability in the trade-space**
  - **Maintained for life**
- **More informative requirements**
- **Well-founded requirements refinement**
- **More alternatives, maintained longer**

Doing so quickly and adaptably requires new technology:

- **Models with representational richness**
- **Learning about operational context**
- **Uncertainty- and Risk- based tools**

Starting point: Model- and Platform- based engineering

Engineered Resilient Systems
Key Technical Thrust Areas

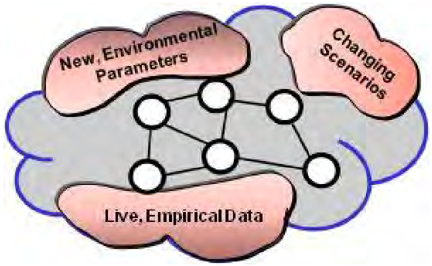


Systems Representation and Modeling

– Capturing physical and logical structures, behavior, interaction with the environment, interoperability with other systems

Characterizing Changing Operational Contexts

– Deeper understanding of warfighter needs, directly gathering operational data, better understanding operational impacts of alternative designs



Cross-Domain Coupling

– Better interchange between "incommensurate" models
– Resolving temporal, multi-scale, multi-physics issues across engineering disciplines

Extended Capabilities →

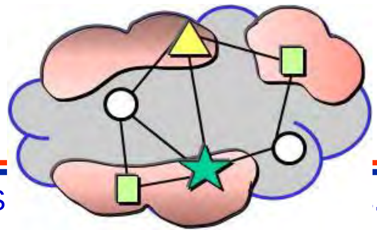
Basic Functions	Baseline	+ Flexibility	+ Robustness	+ Affordability
Structures / Materials	○		□	
Propulsion	○			☆
Aero / Thermal	○			
Electronics	○			
Controls	○		□	
Software	○	△		

Data-driven Tradespace Exploration and Analysis

– Efficiently generating and evaluating alternative designs, evaluating options in multi-dimensional tradespaces

Collaborative Design and Decision Support

– Enabling well-informed, low-overhead discussion, analysis, and assessment among engineers and decisionmakers



System Representation and Modeling: Technical Gaps and Challenges

Technology	10-Yr Goal	Gaps
Capturing • ***Physical and logical structures*** • ***Behavior*** • ***Interaction with the environment and other systems***	**Model 95% of a complex weapons system**	• Combining live and virtual worlds • Bi-directional linking of physics-based & statistical models • Key multidisciplinary, multiscale models • Automated and semi-automated acquisition techniques • Techniques for adaptable models

We need to create and manage many classes (*executable, depictional, statistical...*) and many types (*device and environmental physics, comms, sensors, effectors, software, systems ...*) of models

Characterizing Changing Operational Environments: Technical Gaps and Challenges

Technology	10-Yr Goal	Gaps
Deeper understanding of warfighter needs ***Directly gathering operational data*** ***Understanding operational impacts of alternatives***	**Military Effectiveness Breadth Assessment Capability**	• Learning from live and virtual operational systems • Synthetic environments for experimentation and learning • Creating operational context models (missions, environments, threats, tactics, and ConOps) • Generating meaningful tests and use cases from operational data • Synthesis & application of models

"Ensuring adaptability and effectiveness requires evaluating and storing results *from many, many scenarios* (including those presently considered unlikely) *for consideration earlier* in the acquisition process."

Cross-Domain Coupling: Technical Gaps and Challenges

Technology	10-Yr Goal	Gaps

Better interchange between incommensurate models
 	
Resolving temporal, multi-scale, multi-physics issues
	Weapons system modeled fully across domains	• Dynamic modeling/analysis workflow
		• Consistency across hybrid models
		• Automatically generated surrogates
		• Semantic mappings and repairs
		• Program interface extensions that:
		  • Automate parameterization and boundary conditions
		  • Coordinate cross-phenomena simulations
		  • Tie to decision support
		  • Couple to virtual worlds

Making the wide range of model classes and types work together effectively requires new computing techniques (not just standards)

Tradespace Analysis: Technical Gaps and Challenges

Technology	10-Yr Goal	Gaps
Efficiently generating and evaluating alternative designs ***Evaluating options in multi-dimensional tradespaces***	**Trade analyses over *very large* condition sets**	• Guided automated searches, selective search algorithms • Ubiquitous computing for generating/evaluating options • Identifying high-impact variables and likely interactions • New sensitivity localization algorithms • Algorithms for measuring adaptability • Risk-based cost-benefit analysis tools, presentations • Integrating reliability and cost into acquisition decisions • Cost-and time-sensitive uncertainty management via experimental design and activity planning

Exploring more options and keeping them open longer, by managing complexity and leveraging greater computational testing capabilities

Collaborative Design & Decision Support: Technical Gaps and Challenges

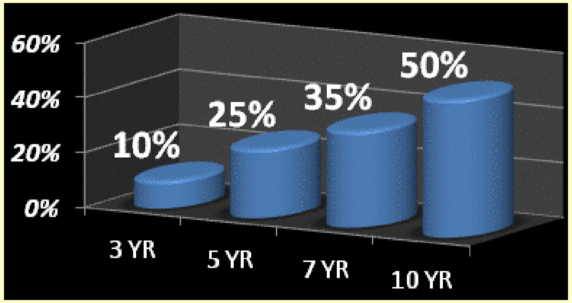
Technology	10-Yr Goal	Gaps
Well-informed, low-overhead collaborative decision making	**Computational / physical models bridged by 3D printing** ***Data-driven* trade decisions executed and recorded**	• Usable multi-dimensional tradespaces • Rationale capture • Aids for prioritizing tradeoffs, explaining decisions • Accessible systems engineering, acquisition, physics and behavioral models • Access controls • Information push-pull without flooding

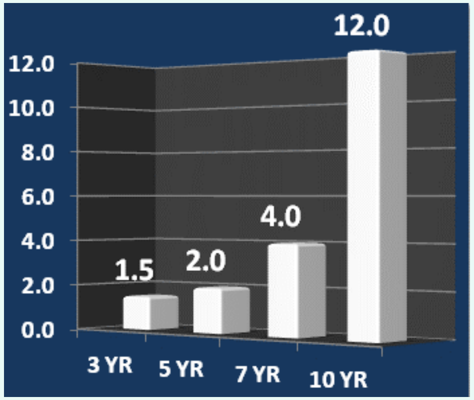
ERS requires the transparency for many stakeholders to be able to understand and contribute, with low overhead for participating

What Constitutes Success?

<u>Adaptable</u> (and thus robust) designs

– Diverse system models, easily accessed and modified
– Potential for modular design, re-use, replacement, interoperability
– Continuous analysis of performance, vulnerabilities, trust
– ***Target: 50% of system is modifiable to new mission***



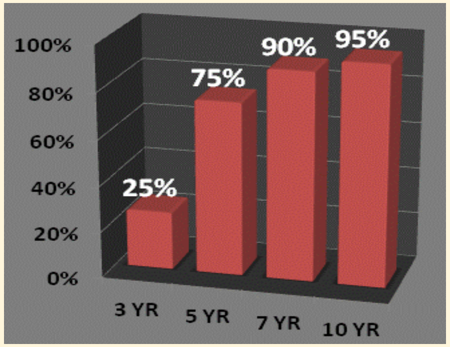


<u>Faster</u>, more efficient engineering iterations

– Virtual design – integrating 3D geometry, electronics, software
– Find problems early:
– Shorter risk reduction phases with prototypes
– Fewer, easier redesigns
– Accelerated design/test/build cycles
– ***Target: 12x speed-up in development time***

Decisions <u>informed</u> by mission needs

– More options considered deeply, broader trade space analysis
– Interaction and iterative design among collaborative groups
– Ability to simulate & experiment in synthetic operational environments
– ***Target: 95% of system informed by trades across ConOps/env.***



Opportunities to Participate
DoD Needs Innovative Tools and Algorithms from Industry and Academia

Organization	BAA Title	Closing Date	Reference #
ONR	Energetic Materials Program R&D	23-Dec-11	12-SN-0001
Dept of Army	Adaptive Vehicle Management System (AVMS) Phase II	6-Jan-12	W911W6-11-R-0013
NAWC Lakehurst	BAA Reconnaissance and Surveillance payloads, sensors, delivery systems and platforms	14-Feb-12	N68335-11-R-0018
NAVFAC	BAA Expeditionary technologies	2-Mar-12	BAA-09-03-RIKA
US Army USACE	2011 BAA	31-Mar-12	W912HZ-11-BAA-02
NRL	NRL-Wide BAA	16-Jun-12	BAA-N00173-01
US Army RDECOM-ARDEC	Technology Focused Areas of Interest BAA	15-Sep-12	W15QKN-10-R-0513
ARL	Basic and Applied Scientific Research	31-Dec-12	W911NF-07-R-0003-04 & -0001-05
Dept of Army	Army Rapid Innovation Fund BAA	29-Sep-12	W911NF11R0017
ONR	BAA, Navy and Marine Corp S&T	30-Sep-12	ONR 12-002
NASC Training Sys Div	R&D for Modeling and Simulation Coordination Office	4-Dec-12	N61339-08-R-0013
AFRL Kirtland	STRIVE BAA	Draft Posted	FA945311R0285
WHS	DoD Rapid Innovation Fund	n/a	HQ0034-RIF-11-BAA-0001
AFRL WPAFB	Reasoning, Comprehension, Perception and Anticipation in Multi-Domain Environments	n/a	BAA-10-03-RIKA
AFRL Rome	Emerging Computing Technology and Applications	n/a	BAA-09-08-RIKA
AFRL Rome	Cross Domain Innovative Technologies	n/a	BAA-10-09-RIKA
AFRL Rome	Computing Architecture Technologies BAA	n/a	BAA-09-03-RIKA
WHS	Systems 2020	n/a	Subject to Presidential Budget Approval

Envisioned End State

Improved Engineering and Design Capabilities

- More environmental and mission context
- More alternatives developed, evaluated and maintained
- Better trades: managing interactions, choices, consequences

Improved Systems

- Highly effective:
  better performance,
  greater mission effectiveness
- Easier to adapt,
  reconfigure or replace
- Confidence in graceful
  degradation of function

Improved Engineering Processes

- Fewer rework cycles
- Faster cycle completion
- Better managed
  requirements shifts

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BACK-UPS

Engineered Resilient Systems S&T Priority Steering Council

AF - Ken Barker, Bill Nolte
Supporting: G. Richard Freeman, Ed Kraft, Sean Coghlan, Kenny Littlejohn, Bob Bonneau, Ernie Haendschke, Mark Longbrake, Dale Burnham, Al Thomas

Army - Jeffery Holland, Kevin Flamm, Elizabeth Burg, Nikki Goerger
Supporting: Dave Horner, Dave Richards, Elias Rigas, Rob Wallace, Robert King, Chris Gaughan, Dana Trzeciak, Lester Strauch

Navy - Bobby Junker, Wen Masters
Supporting: John Tangney, John Pazik, Terry Ericsen, Ralph Wachter (now detailed to NSF), Connie Heitmeyer, Lynn Ewart-Paine, Bill Nickerson Bob Pohanka

DARPA - Chris Earl

OSD – Robert Neches

Engineered Resilient Systems

Mission volatility and uncertain futures necessitate *affordably adaptable & effective systems*

- Adaptable through reconfiguration or replacement
- Affordable from being designed, evaluated, built, and tested faster, with fewer design cycles
- Effective through engineering informed by data-driven evaluations of options and recourses

Adaptability
- Reflected in # of adaptations possible vs new build

Speed of solution
- Relative to current baselines, with many more trades & recourses considered

Informed Designs
- %system design that has included exploration of engineering trades, cost, schedule, CONOPS and environmental variations

Systems Modeling
- 95% coverage of systems and sub-system designs

Characterization of Changing Operational Contexts
- Ability to assess effectiveness of concepts across changing missions, threats, environments

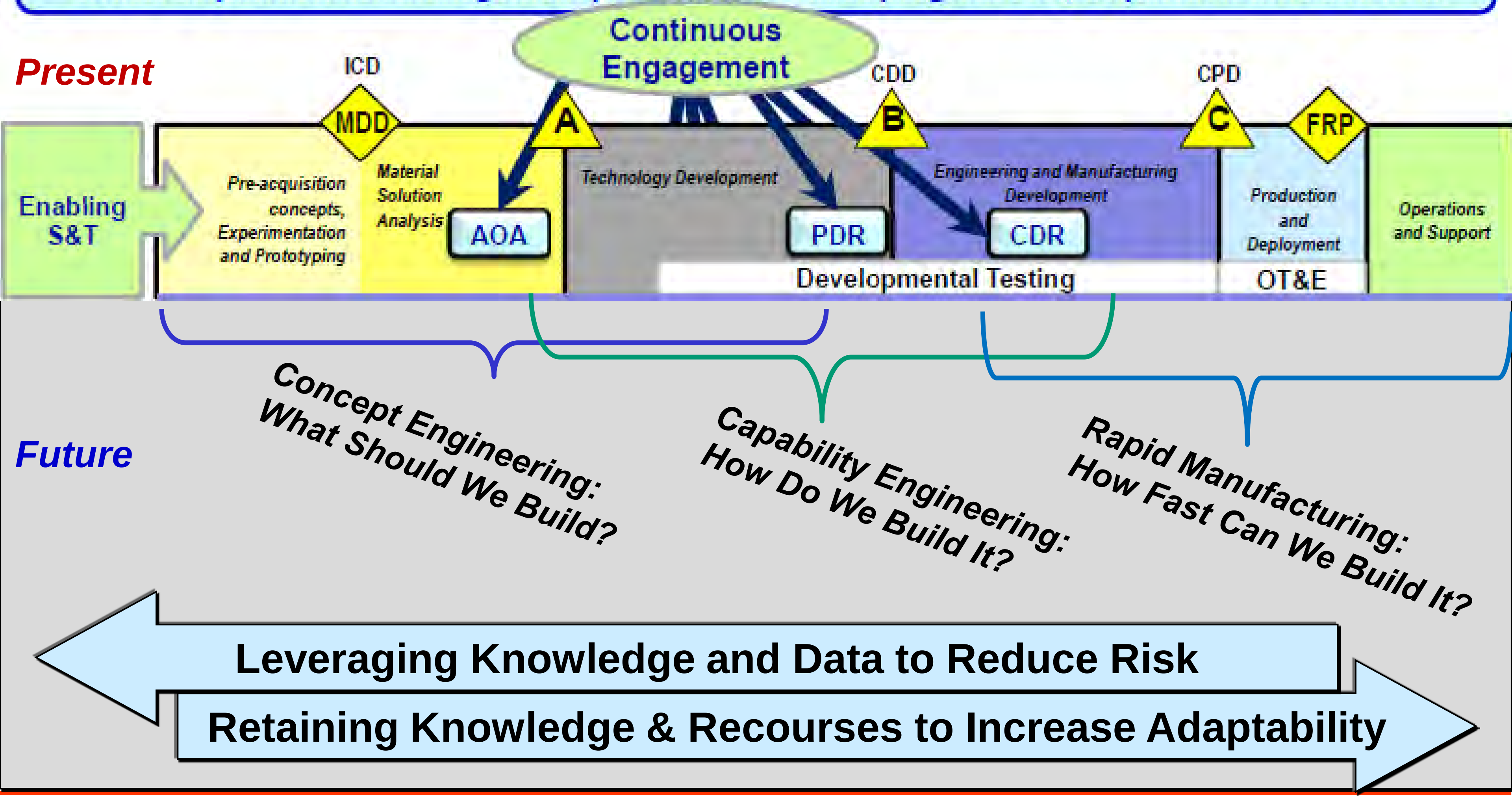
Cross-domain Coupling of Models
- Broad interoperation across disciplines, scales, fidelity levels

Data-driven Tradespace Analysis
- Ability to analyze millions of trades, assess sensitivities & risks

Collaborative Design & Decision Support
- Ability to speed decision processes

Engineered Resilient Systems: Where the Work's Headed

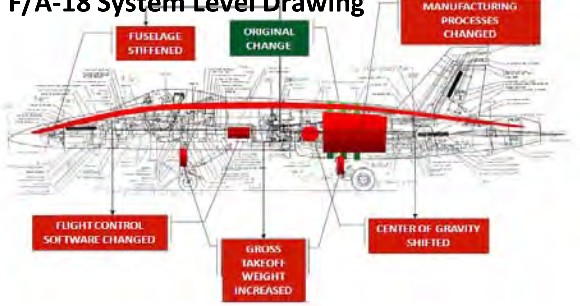
SE has a role in all major acquisition program milestone decisions and oversees and executes critical acquisition risk management processes to reduce program cost, acquisition time and risk.



Example Engineering Shortfalls: Challenges and Opportunities

- Dynamic threats and missions outstripping our ability to specify, design and build responsive systems (IEDs, electronic warfare)
- New concepts of operations not discovered until late in design, or until operational test (Longbow lock-on after launch)
- “Small” engineering changes with unintended consequences (F18)
- Suboptimal trades in performance, reliability, maintainability, affordability, schedule (MRAP, FCS)
- Late discovery of defects (ACS sensors)
- Mismatched engineering tools (787)
- Persistent reliability/availability shortfalls exacerbated by untrusted components

F/A-18 System Level Drawing



Shortfalls point to significant research challenges to improve engineering productivity

Driving Applications Producing New Questions for Next-Gen Engineers

- **Air Maneuver**
- **Ground Vehicles**
- **Electric Ships**
- **Propulsion and Energy Systems**

- **Upgrades & Life Cycle Extension**
- **New Systems**

- **How many operational concepts can this support?**
- **What's the tradeoff between features and diversity?**
- **What are my options, trading capability vs. delivery time?**
- **What're my *adequate* interim options?**
- **If the changing environment invalidates investments, how do we recover?**

Engineered Resilient Systems: "Requirements"

ERS products are engineering tools, methodologies, paradigms that link:

- Conception, design, engineering, prototyping, testing, production, field usage and adaptation
- Engineers, warfighters, industry and other stakeholders

How Do We Get...

Robustness

Efficiency

Options

- **Adaptable (and thus robust) designs**
  - Diverse system models, easily accessed and modified
  - Potential for modular design, re-use, replacement, interoperability
  - Continuous analysis of performance, vulnerabilities, trust
- **Faster, more efficient design iterations**
  - Virtual design, in 3D geometry, electronics, and software combined
  - Find problems early:
    - Reduced risk reduction phases with prototypes
    - Fewer and easier redesigns
  - Accelerated design/test/build cycles
- **Decisions informed by *mission needs***
  - More options considered deeply, broader trade space analyses
  - Interaction and iterative design in context among collaborative groups
  - Ability to simulate and experiment in synthetic operational environments

Emerging Key Concepts

Model-based engineering

+ Open architectures, advanced mathematics

+ User feedback on computational prototyping

+ Collaborative environment for all phases, all stakeholders

+ Deeper tradespace / alternatives analysis

+ Engineering capability enhanced by data, tools, advanced evaluation methods in both live and test environments

+ “Mission utility breadth” as an alternative to point design requirements

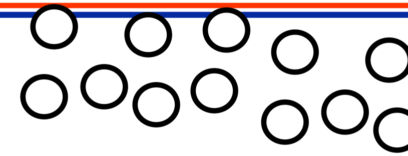
+ Reduced engineering time from intelligent test scheduling

<u>+ Speed and flexibility gains of rapid manufacturing</u>

= Robust systems, efficient engineering, options against uncertain futures

Engineered Resilient Systems
Key Technical Thrust Areas

Systems Representation and Modeling



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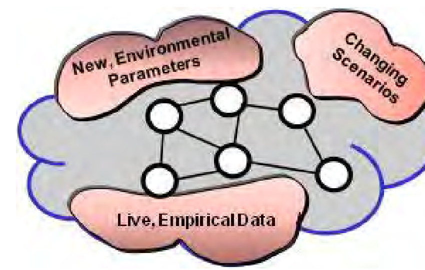
Characterizing Changing Operational Contexts

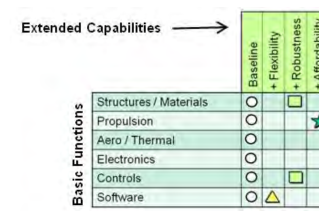
– Deeper understanding of warfighter needs, directly gathering operational data, better understanding operational impacts of alternative designs

Cross-Domain Coupling



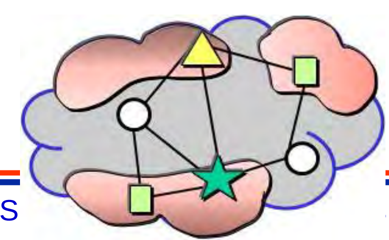
– Better interchange between "incommensurate" models
– Resolving temporal, multi-scale, multi-physics issues across engineering disciplines

Data-driven Tradespace Exploration and Analysis



– Efficiently generating and evaluating alternative designs, evaluating options in multi-dimensional tradespaces

Collaborative Design and Decision Support



– Enabling well-informed, low-overhead discussion, analysis, and assessment among engineers and decisionmakers

ERS Five Tech Enablers

PSC Agreed-upon Definitions (1 & 2)

Systems Representation and Modeling	Specification and analysis of a system and its component elements with respect to its physical and logical structures, its behavior over time, the physical phenomena generated during operation, and its interaction with the environment, and interoperability with other systems.
Characterization of Changing Operational Contexts	Understanding warfighter needs for capability and adaptability. This includes gathering data from users directly, instrumentation of live and virtual operational environments, systems, and system tests. It also includes mechanisms to exploit the data to (a) identify the range of system operational contexts (missions, environments, threats, tactics, and ConOps); (b) better inform designers of their implications; and (c) enable engineers, warfighters and other stakeholders to assess adaptability, sustainability, affordability and timeliness of alternative system designs

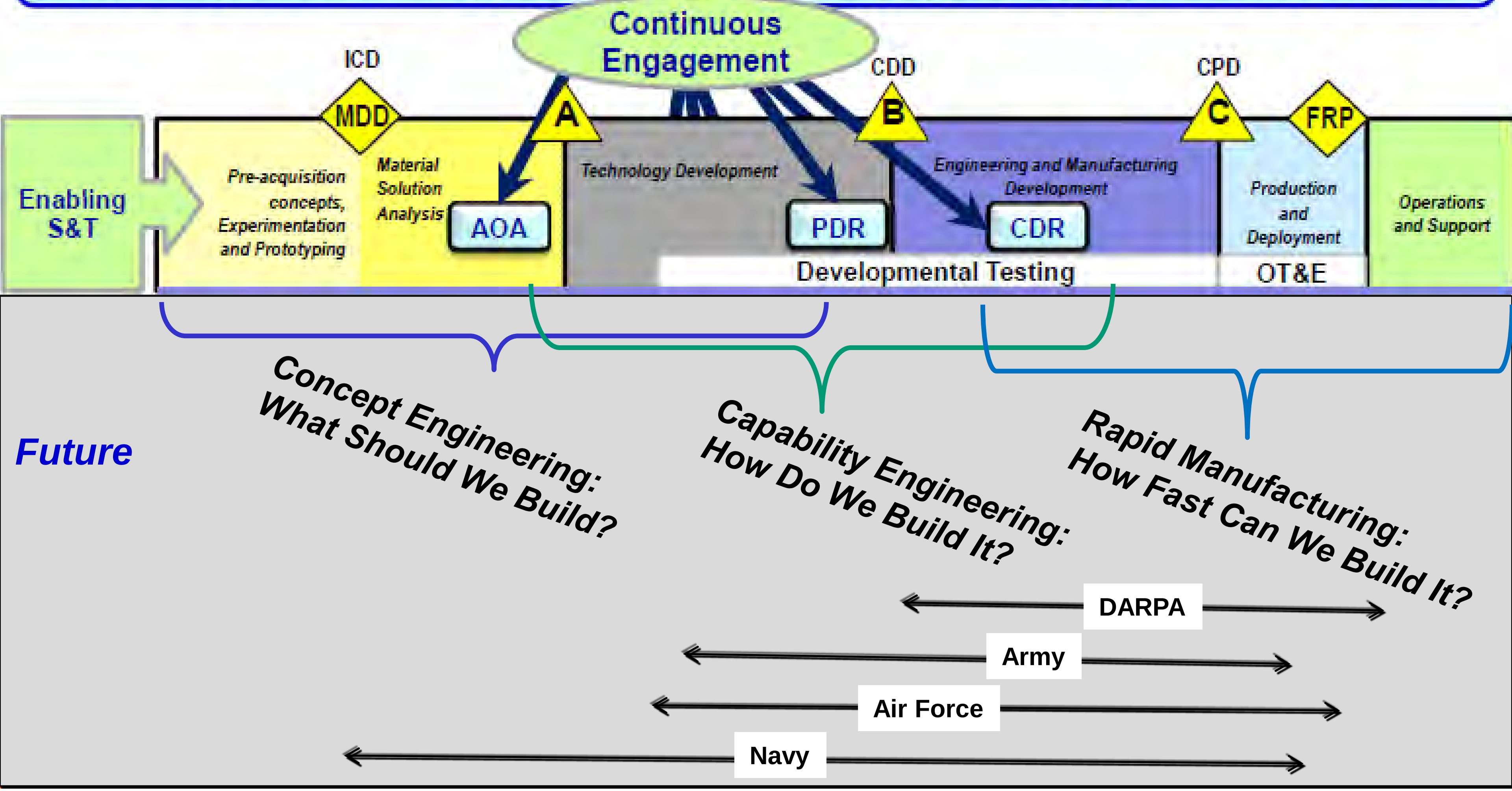
ERS Five Tech Enablers

PSC Agreed-upon Definitions (3,4 & 5)

Cross-Domain Coupling	Interchange of information across "incommensurate" models. Models may be incommensurate because of different temporal or physical granularity within a given discipline, multi-scale/multi-physics issues across different engineering disciplines, or factors arising from differences in intended audience, e.g., abstracting a slower-than-real-time engineering model to drive a real-time gaming system for end users. Cross-Domain Coupling thus subsumes work on interoperability, conversion, abstraction, summarization, and capturing assumptions.
Data-driven Tradespace Exploration and Analysis	Managing the complex space of potential designs and their tradeoffs. Included are: • Tools for generating alternative designs and conducting tradespace analysis • Algorithms for selective search • Tools for performing cost- and time- sensitive design of experiments, and planning of engineering activities to efficiently assess and quantify uncertainty • Tools for evaluating results
Collaborative Design & Decision Support	Tools, methods, processes and environments that allow engineers, warfighters, and other stakeholders to share and discuss design choices. This spans human-system interaction, collaboration technology, visualization, virtual environments, and decision support.

Engineered Resilient Systems: Organizational Ranges of Interest

SE has a role in all major acquisition program milestone decisions and oversees and executes critical acquisition risk management processes to reduce program cost, acquisition time and risk.



Technology Development: Progression of Capability Goals

Technology	3 Yr	5 Yr	7 Yr	10 Yr
System Modeling	Improved and accessible tools linking concept design with physical and electrical system modeling	An approved common framework for system modeling using a variety of tools	Demonstrate ability to model an CWS , 90% realism of subsystems	Demonstrate ability to model an CWS*, 95% realism of subsystems
Cross-Domain Coupling	Cross-scale and some interoperability demonstrated for physical, electrical, and computational domains	Ability to model multi-scale across physical, electrical, & compute domains, for both eng. & ops analyses	Full CWS modeled across domains, sufficient to perform system trades informed by virtual analyses	CWS* modeled fully across domains, include materials, fluids, chemistry, etc.
Characterizing the Changing Environment	Incorporate system model into realistic synthetic environment for user feedback *and* data on system utility	Ability to evaluate varying KPP's of system in synthetic environment for user feedback	Ability to evaluate and trade performance characteristics in synthetic environment across multiple conditions and ConOps	Assessment of CWS* system in military relevant contexts using synthetic environments
Tradespace Development and Analysis	Automated SWaP measurements for multi-domain systems (physical, electrical, software).	Vulnerability analyses of timeliness, reliability & malicious tampering for multiple options in complex systems	Automated analysis of mean time between failures, reliability, and functionality under attack or degradation	Automated trades analysis under wide range of conditions, for realistic CWS* system
Collaborative Design and Decision Support	Reference framework & environment for distributed system modeling	Multi-user , multi-design, multi-context system evaluations in synthetic environments	3-D visualizations, realistic conops for evaluation and training, virtual reality experience for CWS* system	Computational/physical models bridged by 3D printing; data-driven CWS* trade decisions enabled, executed and recorded by ERS

* CWS = Complex Weapons System

ERS Roadmap: Relation of Capabilities to Metrics

Engaging DoD, Academic & Industry R&D Initiatives

Measure	3 Yr	5 Yr	7 Yr	10 Yr
Adaptability of Design ***Percentage of original system adapted or modified in response to new missions***	10%	25%	35%	50%
Speed of Design Solution ***Response time improvement, relative to baseline time for fixed time upgrade***	1.5x	2x	4x	12x
Informed Design: Breadth ***Percentage of system "informed" by models and trades that include CONOPs and environment exploration of potential Fielded Systems***	25%	75%	90%	95%

Model- and Platform-based engineering enables both alternative exploration and adaptability

** CWS = Moderately Complex Weapons System*

43 Currently Identified Related Programs Across DoD

- **Army**
  1. C4ISR On the Move -- CERDEC
  2. Institute for Maneuverability and Terrain Physics (IMTPS)
  3. Institute for Creative Technologies (ICT) University Affiliated Research Center (UARC)
  4. MATREX (Modeling Architecture for Technology, Research and EXperimentation) -- RDECOM
  5. Supply Chain Risk Management (SCRM) -- SMDC
  6. Condition-based maintenance and prognostics -- AMRDEC
  7. GEOTACS --ERDC
  8. DEFeat of Emerging Adaptive Threats
  9. Safe Operations of Unmanned systems for Reconnaissance in Complex Environments (SOURCE) Army Technology Objective
  10. Quick Reaction and Battle Command Support Division, CERDEC
  11. Concepting, Analysis, Systems Simulation & Integration (CASSI) Future Combat Systems (FCS) Mounted Combat System (MCS) -- TARDEC
  12. CASSI TARDEC
  13. AMRDEC Prototype Integration Facilty

- **DARPA**
  1. META: Adaptable Low Cost Sensors; FANG: Fast, Adaptable, Next Generation Ground Combat Vehicle; iFAB
  2. M-GRIN: Manufacturable Gradient Index Optics
  3. IRIS: Integrity and Reliability of Integrated Circuits
  4. Open Manufacturing

- **OSD**
  1. Systems 2020
  2. Systems Engineering Research Center

- **Naval Research**
  1. Formal design analysis, NRL
  2. Sensor system platform
  3. Future Immersive Training Environment (FITE), Navy JCTD
  4. Basic Research on Tradeoff Analysis, Behavioral Economics, Navy
  5. PSU ARL Tradespace Tools
  6. Night Vision Integrated Performance Model
  7. Unmanned Systems Cross-Functional Team
  8. Architectures, Interfaces, and Modular Systems (AIMS)
  9. NSWC Dahlgren Strategic and Weapon Control Systems Dept
  10. Platform Optimization Tools
  11. Command & Control Rapid Prototype Capability (C2RPC)
  12. Virtual World Exploration & Application Program
  13. ONR 331 M&S for System Optimization for the All Electric Warship
  14. Electric Ship R&D Consortium

- **Air Force**
  1. Network Systems and Mathematics
  2. Measurement-Based Systems Verification
  3. Trusted Silicon Stratus, AFRL/RIT
  4. CREATE-AV
  5. Service Oriented Architecture for Command and Control
  6. Condition-based Maintenance
  7. Advanced Manufacturing Enterprise
  8. Condition-based maintenance and prognostics
  9. INVENT System Integration Facility: Robust Electrical Power System; High Performance Electric Actuation System; Adaptive Power & Thermal Maanagement System
  10. Architecture Modeling and Analysis for Complex Systems, AFRL/RY

Issues in Building an Engineered Resilient Systems S&T Community

- **Complex integration across many technologies:**
  - Interdisciplinary across air, land, sea for electromechanical systems with embedded control computational capabilities
  - Spans the engineering lifecycle: Concept engineering and analysis, Design & Prototyping, Development, Production, Sustainment
  - New tools, methods, paradigms:
    Linking engineers, decisionmakers, other stakeholders
  - Addressing product *robustness*, engineers' *productivity*, and systemic *retention of options*

- **Nascent, emerging ties to basic science, e.g.:**
  - Computational Approximate Representations:
    Can't get all engineering tools talking same language
  - Mathematics and Computational Science of Complexity:
    Can't look at every engineering issue, need aids to determine focus
  - Mathematics and Cognitive Science of Risk, Sensitivity, and Confidence:
    Need decision aids for understanding implications of trades, committing $

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