Advanced Planning & Integration Office

Systems Engineering Cost/Risk Analysis Capability Roadmap Progress Review

Stephen Cavanaugh, NASA Chair
Dr. Alan Wilhite, External Chair

April 6, 2005

Agenda

Time	Topic	Speaker
7:30	Continental Breakfast	
8:00	Welcome and Review Process, Panel Chair & NRC Staff	
8:15	NASA Capability Roadmap Activity	Vicki Regenie, NASA
8:30	15.0 Systems Engineering Cost/Risk Analysis Overview	Stephen Cavanaugh, NASA
	-Sub-Team Presentations-	
9:00	15.1 Systems Engineering	Dr. Alan Wilhite, Georgia Tech
	- Break -	
11:15	15.2 Life Cycle Costing	Dr. David Bearden, Aerospace Corporation
12:00	***– Lunch –***	
12:45	15.3 Risk Management	Theodore Hammer, NASA
1:30	15.4 Safety and Reliability Analysis	Dr. Homayoon Dezfuli, NASA
2:15	Concluding Summary	Stephen Cavanaugh, NASA
	- Break -	
3:00	Open Discussion	NRC Panel

SE Capability Roadmap Team

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Co-Chairs
NASA: Stephen Cavanaugh, LaRC
External: Dr. Alan Wilhite, Georgia Tech

Team Members

Government	Industry	Academia
Dr. Michael Gilbert, LaRC	Dr. David Bearden, Aerospace	Dr. Alan Wilhite, Georgia Tech
Theodore Hammer, HQ	Dr. Leonard Brownlow, Aerospace	
Dr. Homayoon Dezfuli, HQ	Gaspare Maggio, SAIC	
Stephen Creech, MSFC	Steven Froncillo, SAIC	
Phil Napala, HQ		
CAPT Daven Madsen, Navy/NSSO		
Dr. Steve Meier, NRO		
Richard Westermeyer, Navy/NSSO		

Consultants
Stephen Kapurch, HQ
David Graham, HQ
Dale Thomas, MSFC
Stephen Prusha, JPL
Chuck Wiesbin, JPL
Ron Moyer, HQ

Coordinators
Directorate: Vicky Hwa, HQ Technical
Doug Craig, HQ Integration
Betsy Park, HQ Integration
APIO: Victoria Regenie, DFRC

Capability Definitions

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- ***Systems engineering*** **is a robust approach to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk.**

- ***Life-Cycle Cost*** **is an integrated, process-centered, and disciplined approach to life cycle management of projects providing real and tangible benefits to all project stakeholders.**

- ***Risk Management*** **identifies potential problem areas early enough to allow development and implementation of mitigation strategies to control cost, schedule and mission success.**

- ***Safety and Reliability Analysis*** **maximizes Mission Success while managing safety risk and affordably meeting mission objectives.**

Capability Roadmap Breakdown Structure

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SE, Cost & Risk Analysis 15.0

NASA Chair: Steve Cavanaugh (LaRC)
External Chair: Dr. Alan Wilhite (Georgia Tech)

- **Systems Engineering** 15.1 — Lead: Dr. **Alan Wilhite/GT**
  - Engineering 15.1.1
  - Support 15.1.2
  - Process Management 15.1.3
  - Project Management 15.1.4
- **Life Cycle Costing** 15.2 — Lead: Dr. **Dave Bearden /Aerospace**
  - Tools 15.2.1
  - Skills 15.2.2
  - Process 15.2.3
- **Risk Management** 15.3 — Lead: **Ted Hammer/HQ**
  - Prepare for Risk Management 15.3.1
  - Identify & Analyze Risks 15.3.2
  - Mitigate Risks 15.3.3
- **Safety & Reliability Analysis** 15.4 — Lead: **Dr. Homayoon Dezfuli/HQ**
  - System Safety 15.4.1
  - System Reliability 15.4.2
  - Safety Management 15.4.3

This Capability Roadmap scope does not include performing the integration of all fifteen Capability Roadmaps. Roadmap coordinators (MD, Center, & APIO) comprise the Integration Team and facilitate the integration process by capturing Roadmap data and dependencies and documenting in relational database tool.

Need for Systems Engineering

- The President has challenged NASA to undertake exploration of the solar system
- In the face of tight budgets and mission risks, it is critical that these missions be executed flawlessly
  - Requires sound approach to Systems Engineering
    - Tools, methods, processes
      - Continuous improvement
    - Best of industry and government
    - Standard processes
      - All centers
      - All missions
      - All programs/projects
- System Engineering must be a “value added proposition” not an overhead burden
  - Consistent with the spirit of CAIB Recommendation

NASA’s new vision requires, more than ever, excellence in an integrated systems engineering cost/risk analysis capability

Four Systems Engineering Essentials

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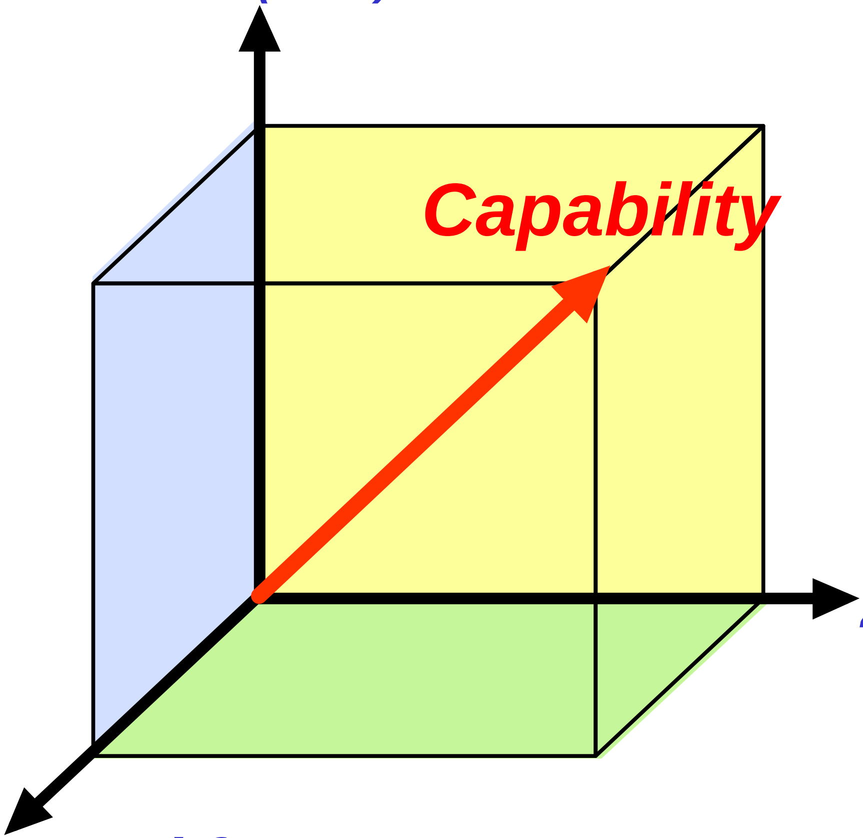
1st – Processes & Concepts

(What)



4th – How well organization implements and supports the framework with:

- Policies & Procedures
- Process Improvement
- Human Resources
- Training
- Milestone & Decision Gate Review Criteria
- Management of Quality

2nd - Performance Aids

(How)

3rd - Workforce

(Who)

Complexity is a Major Issue

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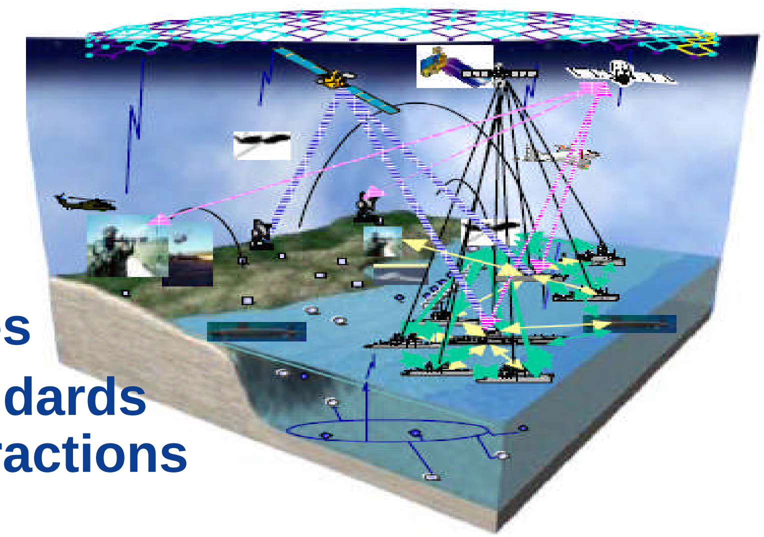
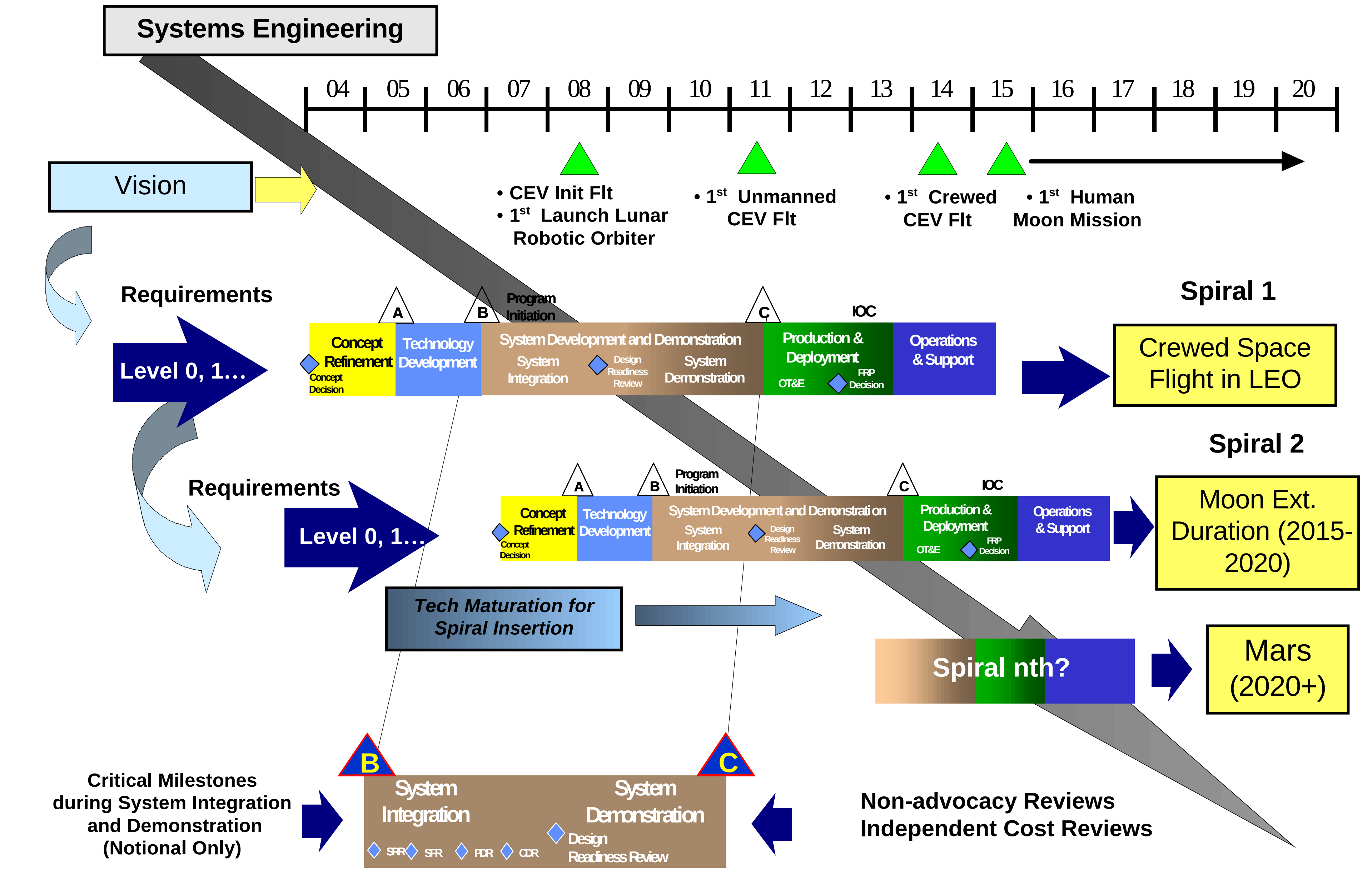
- **Systems-of-Systems are Complex**
  - As More Systems Are Added, the Interfaces Grow in a Non-Linear Fashion
  - Many of the Existing Systems Are Old and Not Built for These Interfaces
  - Conflicting or Missing Interface Standards Make It Hard to Define Interface Interactions



- **Systems Engineering Must Deal With This Complexity**
  - End-to-End Systems Engineering Is Needed, Including "Reengineering" Of Old Systems
  - Robust M&S, Verification And Validation Testing Are A Must
  - Need To Upgrade Modeling And Simulation Tools For Both Concept Definition And Verification And Validation Phases

Reference: 23 Feb. 2005 - James R van Gaasbeek
Northrop Grumman Integrated Systems

Project Constellation Timeline



Why is this Capability important?

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September 21, 2004 Letter from the National Academies

Dear RADM Steidle:

At your request, the National Research Council recently established the Committee on Systems Integration for Project Constellation.

The following quotes were taken from the report:

“Strengthening the state of systems engineering is also critical to the long-term success of Project Constellation. A competent systems engineering capability must be resident within the government and industry”.

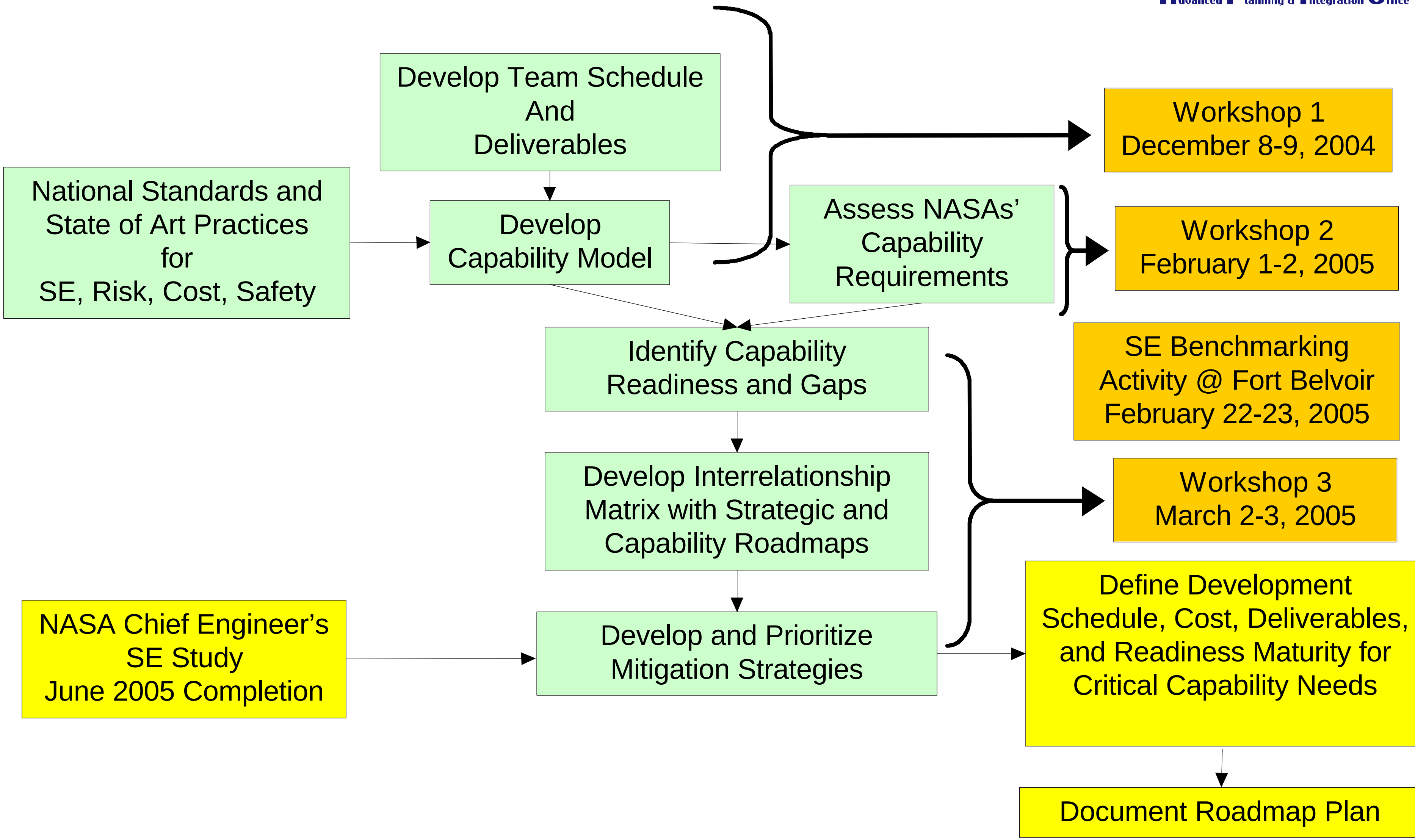
“NASA’s human spaceflight systems engineering capability has eroded significantly as a result of declining engineering and development work, which has been replaced by operational responsibilities”.

“The demand for experienced systems engineers, who can function credibly in a system-of-systems environment, is particularly acute”.

“*Plans should be developed for maintaining a satisfactory base of systems engineering throughout the duration of this program”.*

- "Systems Integration" Will Take Place At Multiple Tiers
  - Tiers structured around functional responsibilities
  - Must be prepared to support with maximum efficiency, minimum bureaucracy
  - Need to support Directorate and Technology Themes, as well as Constellation
  - SE&I authority should reside at lowest possible level
- System-of-Systems Integration Demands Creative Solution
  - No single model evaluated by NRC offers complete solution
  - Complete expertise and competence is not available in any one sector
  - Certain functions can only be executed by government personnel
  - "Hybrid model" using government, FFRDC, and industry is attractive
- ESMD SE&I Capability Will Be Phased-In Over Time
  - Government will perform SE&I work needed to complete Spiral 1 SRR
  - Near-term solution may evolve to different Long-term solution

Capability Roadmapping Process & Approach



Basis for Assessment

- Quality Function Deployment (QFD)
  - A quality system that implements elements of Systems Thinking (viewing the development process as a system) and Psychology (understanding customer needs
- Benchmarking – Chief Engineers Fort Belvoir Workshop on February 22-23, 2005
  - Learning from the experience of others in Industry, DoD, and Other Agencies
- Literature Search – mostly Internet
- Limitations of Assessment
  - Budget limitations keep team small and limited in scope
  - QFD assessment limited to team size – small sample of NASA
  - Assessment more Qualitative vs. Quantitative

Capability Readiness Rating for process, tools, and skills

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Team Gap Assessment

Minor or No Gap

Significant Gap

Critical Gap

APIO Capability Readiness Levels

7 Capability Operational Readiness

6 Integrated Capability Demonstrated in an Operational Environment

5 Integrated Capability Demonstrated in a Relevant Environment

4 Integrated Capability Demonstrated in a Laboratory Environment

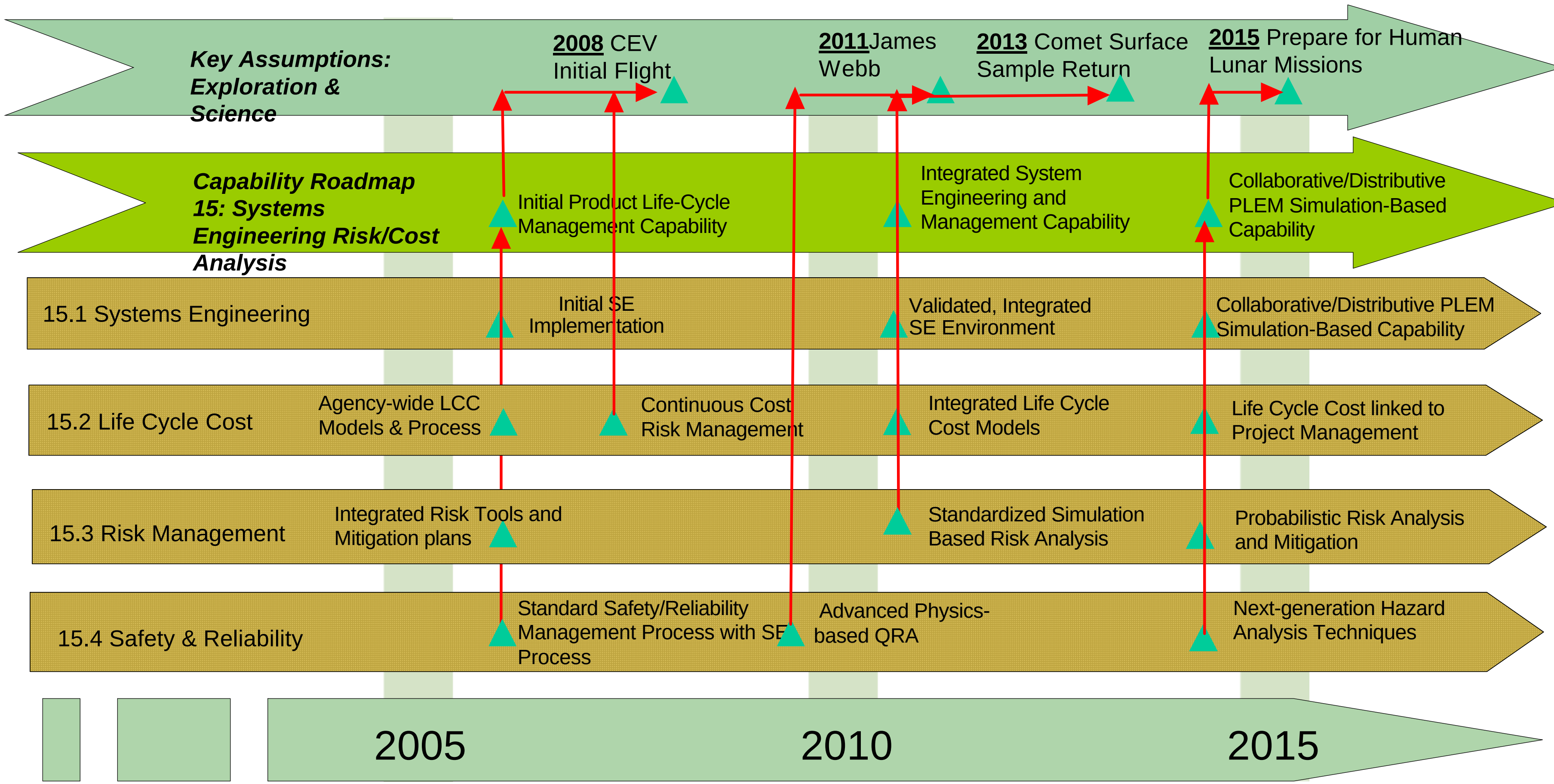
3 Sub-Capabilities* Demonstrated in a Relevant Environment

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

Capability readiness rating assignments are intended for future exploration missions and as such they should not be interpreted as capability ratings to perform the current missions.

Capability Team 15: Systems Engineering Top Level Capability Roadmap



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Capability Team 15: Systems Engineering Top Level Capability Roadmap

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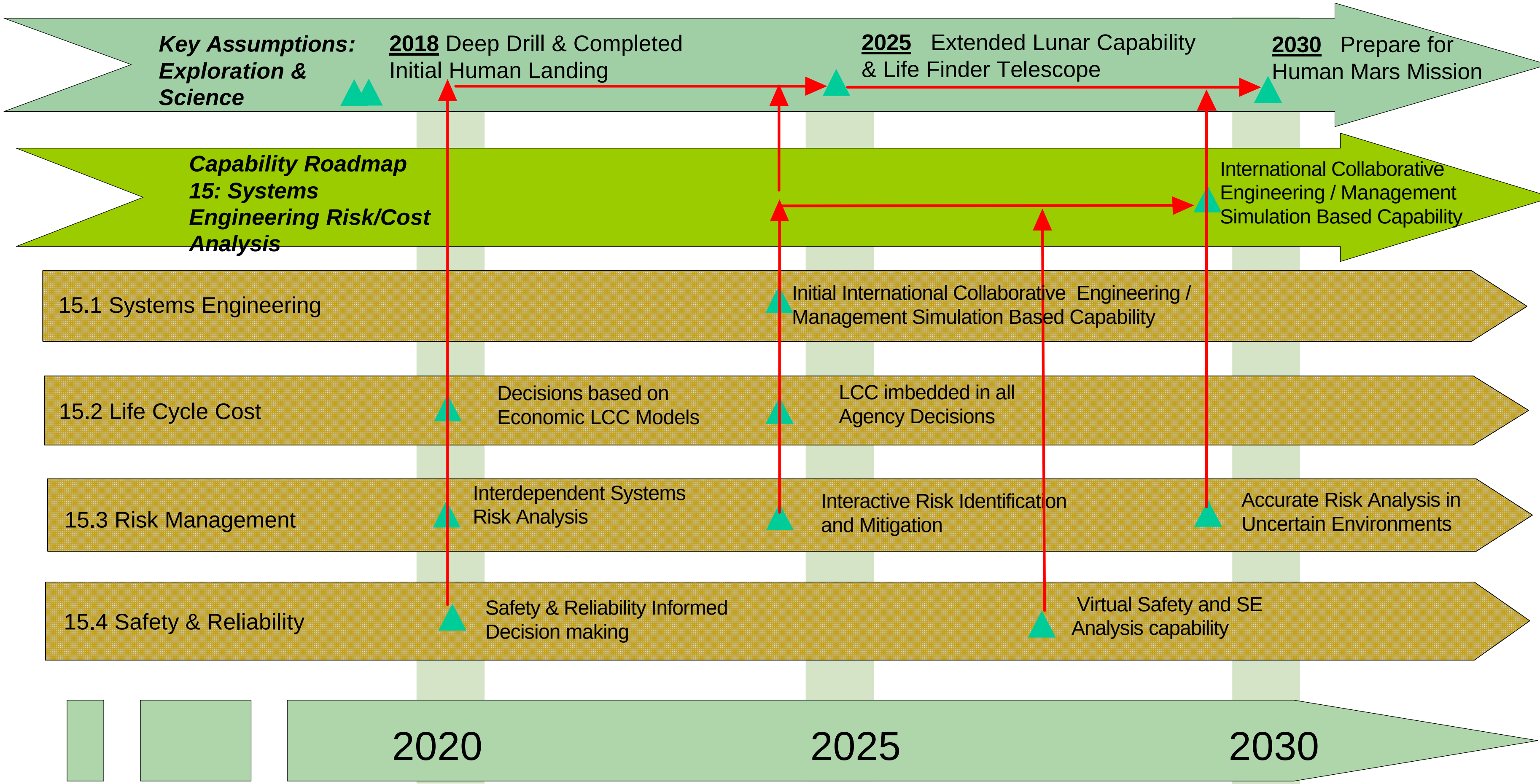

Major Decision

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Legend

PLM – Product Life Cycle Management
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Future State Required to Meet NASA Exploration Vision

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- **Process (What)** – Need a common process for Systems Engineering, Cost, Risk and Safety. NASA Policy Requirements, guidelines and handbooks for this Capability need to be developed along with a need for an audible process.
- **Tools (How)** – Need a standardized approach for Systems Analysis. This includes a framework for advanced tools.
- **People (Who)** – Need qualified personnel. Training & Education programs including certification tied to job criteria and performance standards.

> ***"An immediate transformation imperative for all programs is to focus more attention on the application of Systems Engineering principles and practices throughout the system life cycle"***
>
> **USAF Chief of Acquisition Memo, "Incentivizing Contractors for Better Systems Engineering, 9 Apr 03**

Capability 15.1 Systems Engineering

Presenter:

Dr. Alan Wilhite

Benefits of Systems Engineering

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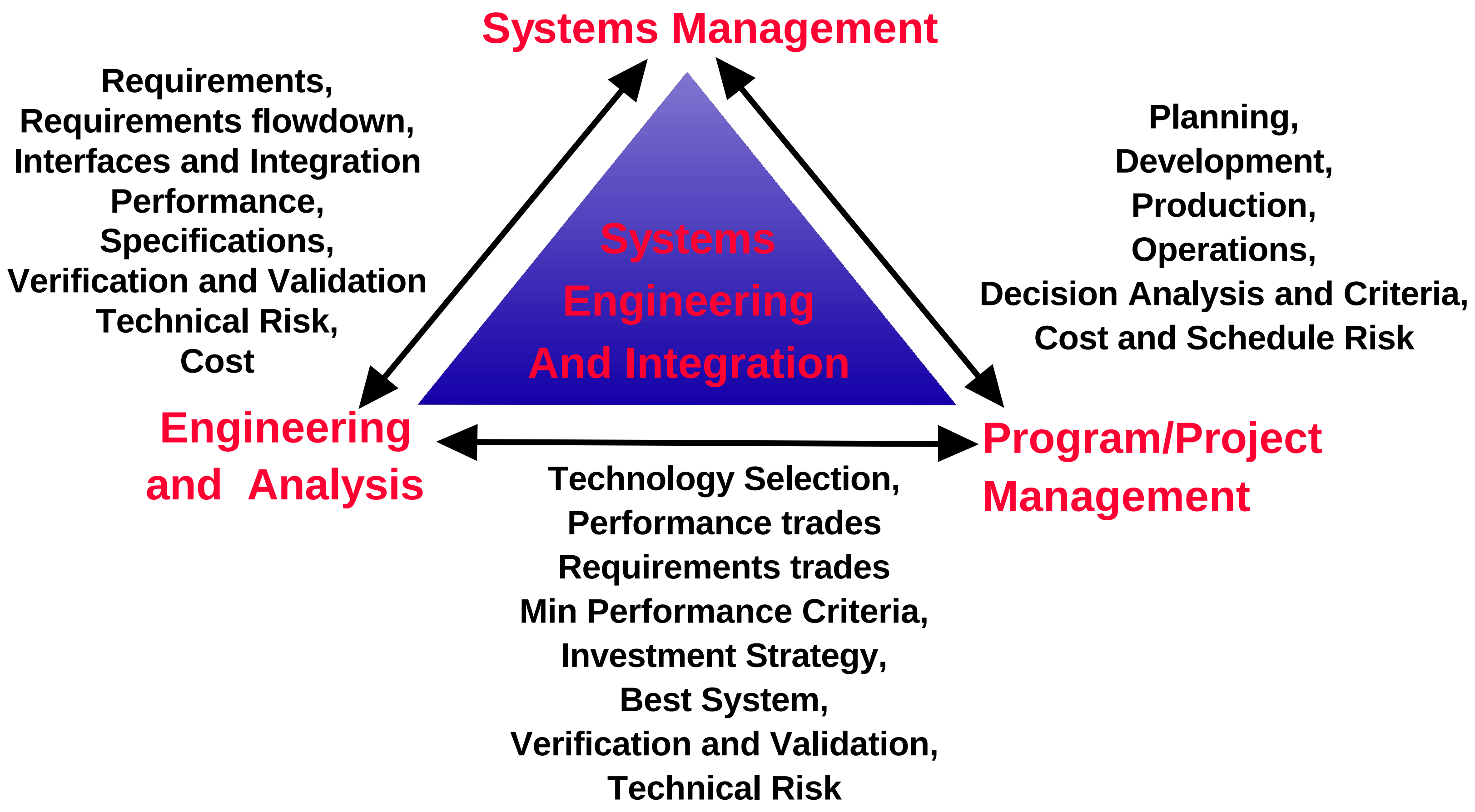
- Requirements driven – build the right system
- Process driven – build the system right
- Integrated engineering and management for informed decisions
- Less cost / Less duration

Systems Engineering and Integration



Ref. GaTech AE 6322

The Systems Engineering Process
(Ref. Mil STD 499B)

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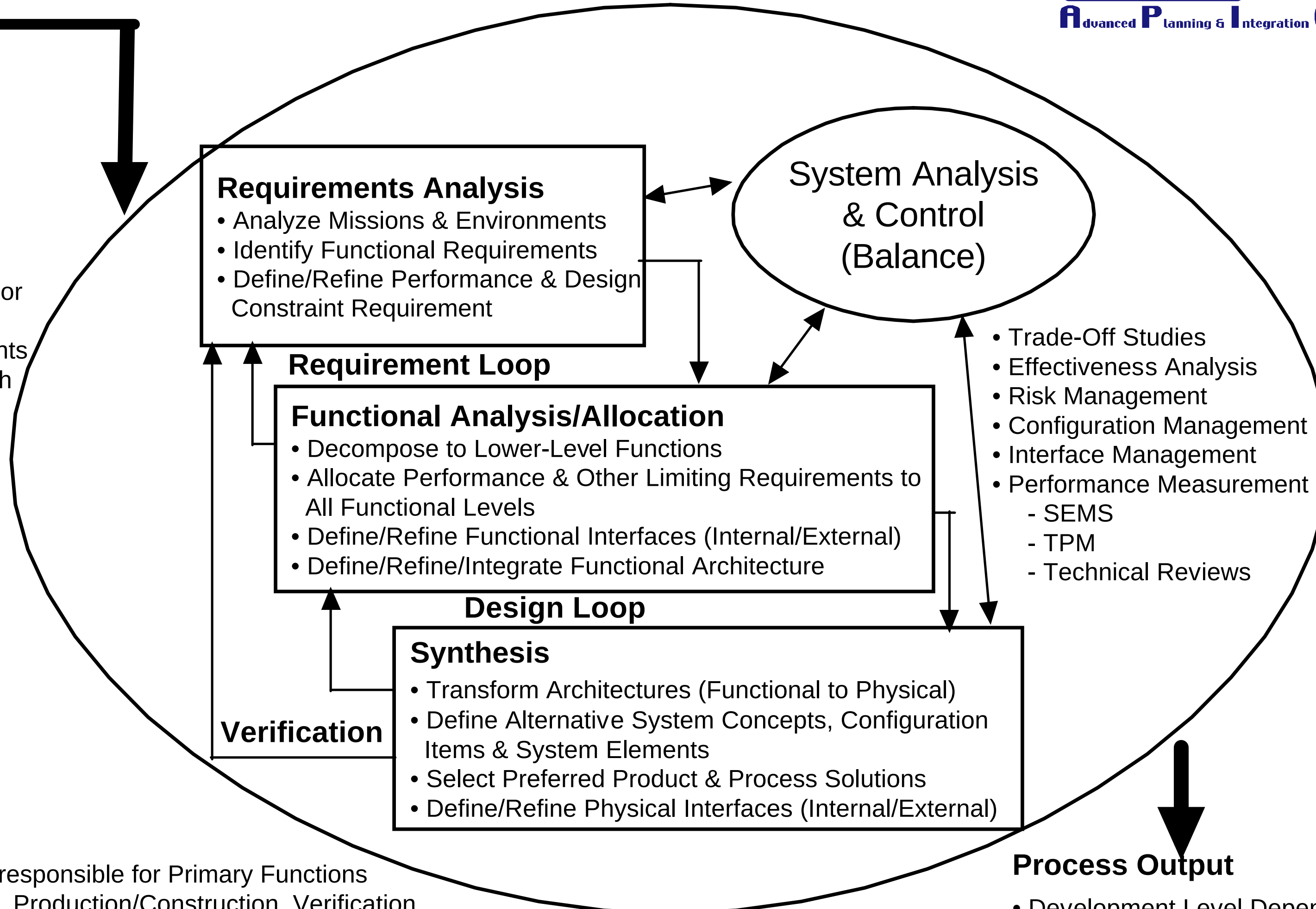
Process Input

- Customer Needs/Objectives/ Requirements
  - Missions
  - Measures of Effectiveness
  - Environments
  - Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards



Related Terms:

Customer = Organization responsible for Primary Functions

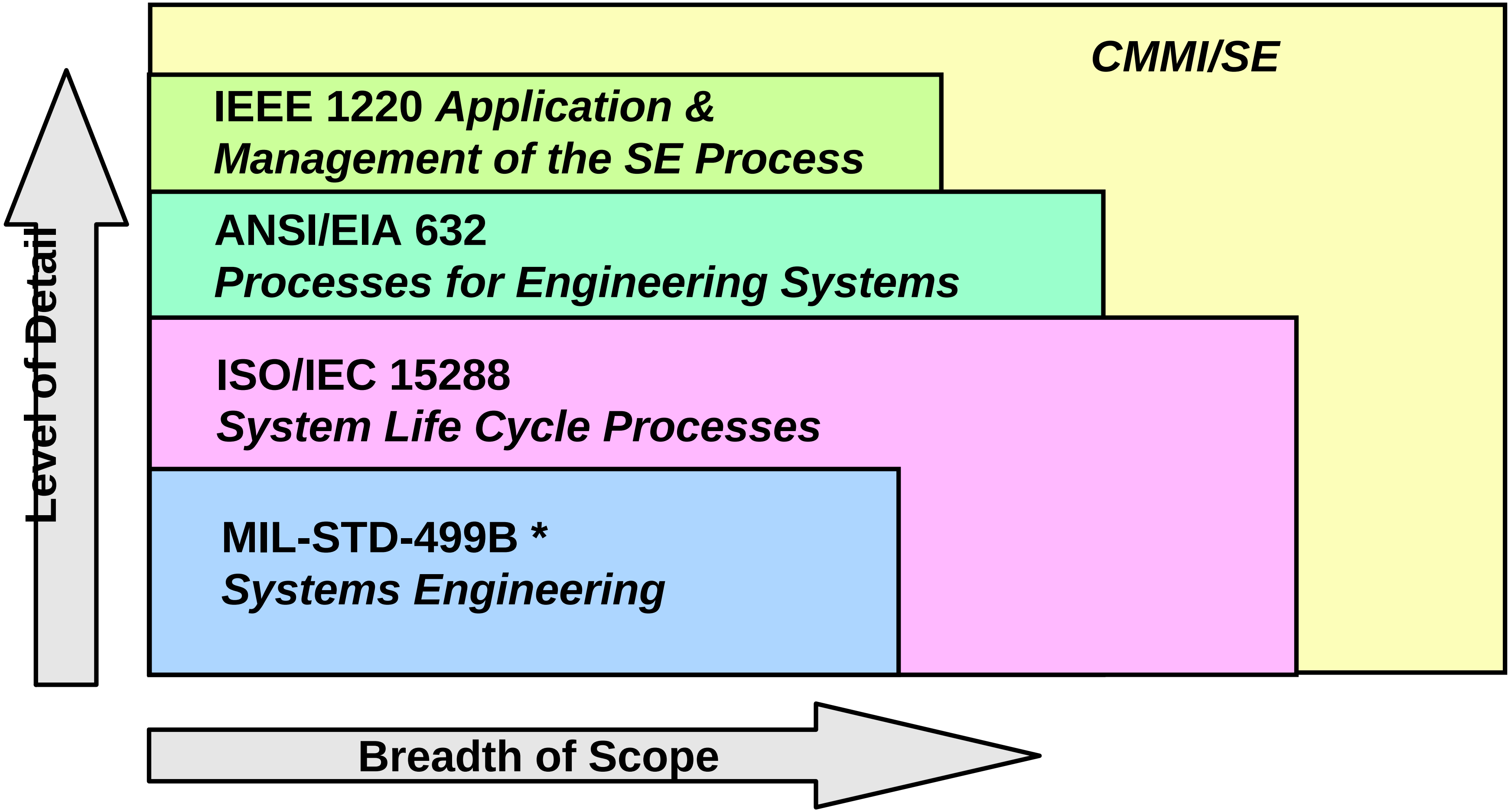
Primary Functions = Development, Production/Construction, Verification, Deployment, Operations, Support Training, Disposal

Systems Elements = Hardware, Software, Personnel, Facilities, Data, Material, Services, Techniques

Process Output

- Development Level Dependant
  - Decision Data Base
  - System/Configuration Item Architecture
  - Specification & Baseline

Scope of SE Standards



* Mil-Std-499C has more detail (similar to 15288) than Mil-Std 499B and has more breadth (similar to IEEE 1220)

Capability Maturity Model Integration

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CMMI – DoD developed integrated model for systems engineering, software engineering, integrated product process development, and supplier sourcing

CMMI

Process Management

- Organizational Process Focus
- Organizational Process Definition
- Organizational Training
- Organizational Process Performance
- Organizational Innovation and Deployment

Project Management

- Project Planning
- Project Monitoring and Control
- Supplier Agreement Mgmt.
- Integrated Project Mgmt.
- Integrated Supplier Management
- Risk Management
- Quantitative Project Mgmt.
- Integrated Teaming

Engineering

- Requirements Management
- Requirements Development
- Technical Solution
- Product Integration
- Verification
- Validation

Support

- Configuration Mgmt.
- Process and Product Quality Assurance
- Measurement & Analysis
- Decision Analysis and Resolution
- Causal Analysis and Resolution
- Organizational Environment for Integration

CMMI used as initial basis for strategic planning

Overview of the "State"

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- The Standish Group (which exists solely to track IT successes and failures) surveyed 13,522 projects in 2003 and showed the following:
  - 34% of projects succeed (these projects are defined as those which deliver the contracted capabilities on time and on budget).
  - 15% of projects are out and out failures (these projects are defined as those abandoned midstream)
  - The rest (51%) are "challenged", meaning over budget, and/or over schedule, and/or deliver less capability / functionality than agreed upon and contracted for.
- According to a Lake & Sheard paper
  - Systems Engineering is practiced in a quagmire of SE Standards
    - MARC Proceedings 1999
- According to the AF Center for Systems Engineering:
  - "Systems Engineering is not broken."
    - GEIA-G47 meeting January 2005

Ref: Lake Briefing at February 2005 Ft Belvoir NASA Chief Engineer Workshop

Systems Engineering is not broken but needs significant advancement to improve NASA's program success rate

System Engineering Processes

SE Capability Team Assessment

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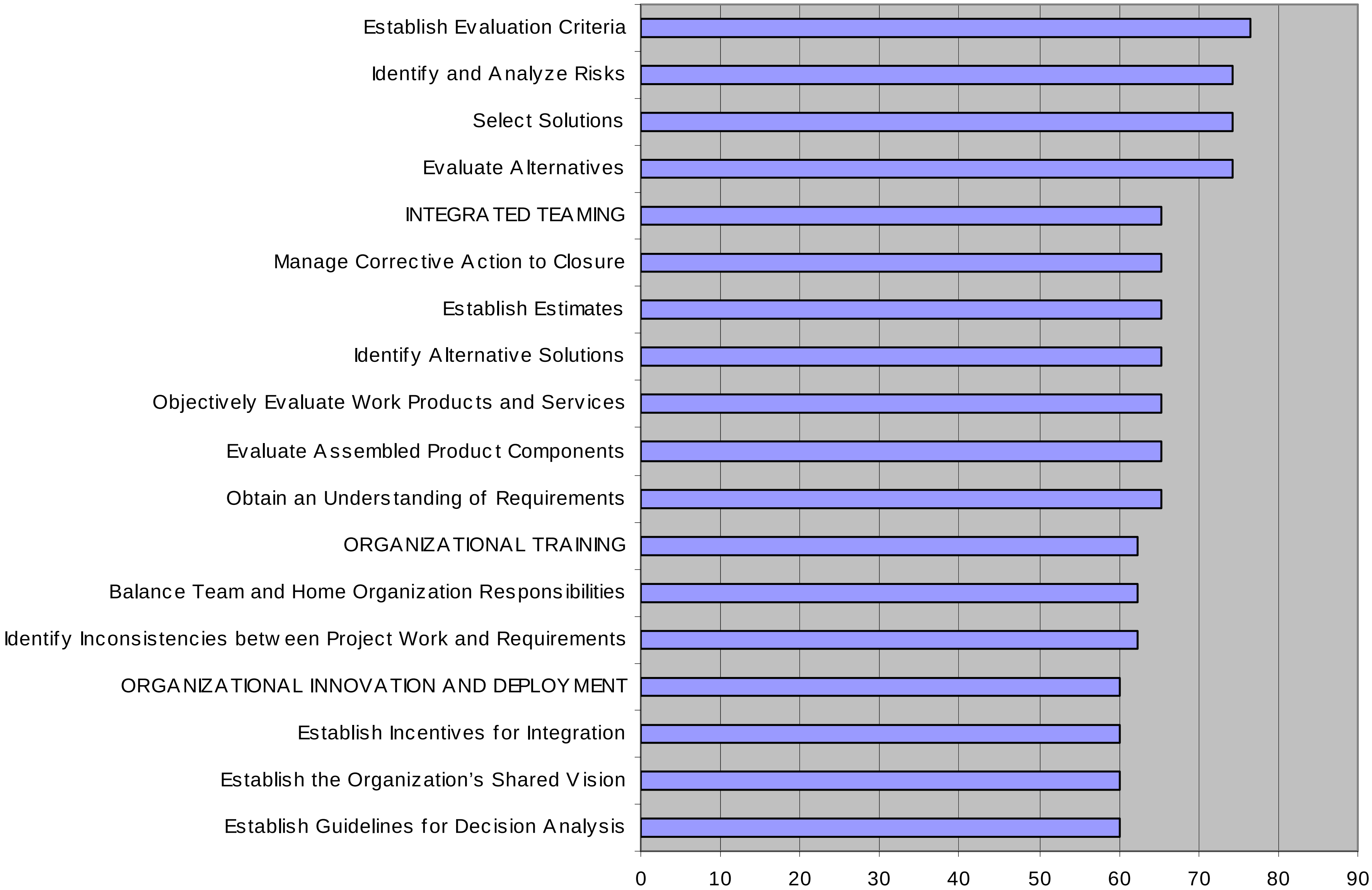
SE-CMMI			Team Assessment
	ENGINEERING		
		REQUIREMENTS DEVELOPMENT	
		REQUIREMENTS MANAGEMENT	
		TECHNICAL SOLUTION	
		PRODUCT INTEGRATION	
		VERIFICATION	
		VALIDATION	
	PROJECT MANAGEMENT		
		PROJECT PLANNING	
		PROJECT MONITORING AND CONTROL	
		SUPPLIER AGREEMENT MANAGEMENT	
		INTEGRATED PROJECT MANAGEMENT FOR IPPD	
		RISK MANAGEMENT	
		INTEGRATED TEAMING	
		INTEGRATED SUPPLIER MANAGEMENT	
		QUANTITATIVE PROJECT MANAGEMENT	
	SUPPORT		
		CONFIGURATION MANAGEMENT	
		PROCESS AND PRODUCT QUALITY ASSURANCE	
		MEASUREMENT AND ANALYSIS	
		DECISION ANALYSIS AND RESOLUTION	
		ORGANIZATIONAL ENVIRONMENT FOR INTEGRATION	
		CAUSAL ANALYSIS AND RESOLUTION	
	PROCESS MANAGEMENT		
		ORGANIZATIONAL PROCESS FOCUS	
		ORGANIZATIONAL PROCESS DEFINITION	
		ORGANIZATIONAL TRAINING	
		ORGANIZATIONAL PROCESS PERFORMANCE	
		ORGANIZATIONAL INNOVATION AND DEPLOYMENT	

Integrated rollup of Importance and Present Capability

Critical Gap	
Significant Gap	
No or Minor Gap	

Detail of Capability Assessment
(Top 10% out of 187 processes)



Other Identified SE Capability Gaps

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Systems of Systems Integration	
Experienced SE Personnel	
Standard Process/Process Improvement	
Facilitate Advanced Technology	
Estimate and Manage Costs	
Acquisition Strategy	
Advanced Collaborative Environment	

Refs.

- NRC SE&I Study, 2004
- NASA SE Workshop, 2005

Critical Gap	
Significant Gap	
No or Minor Gap	

Quagmire of SE Standards

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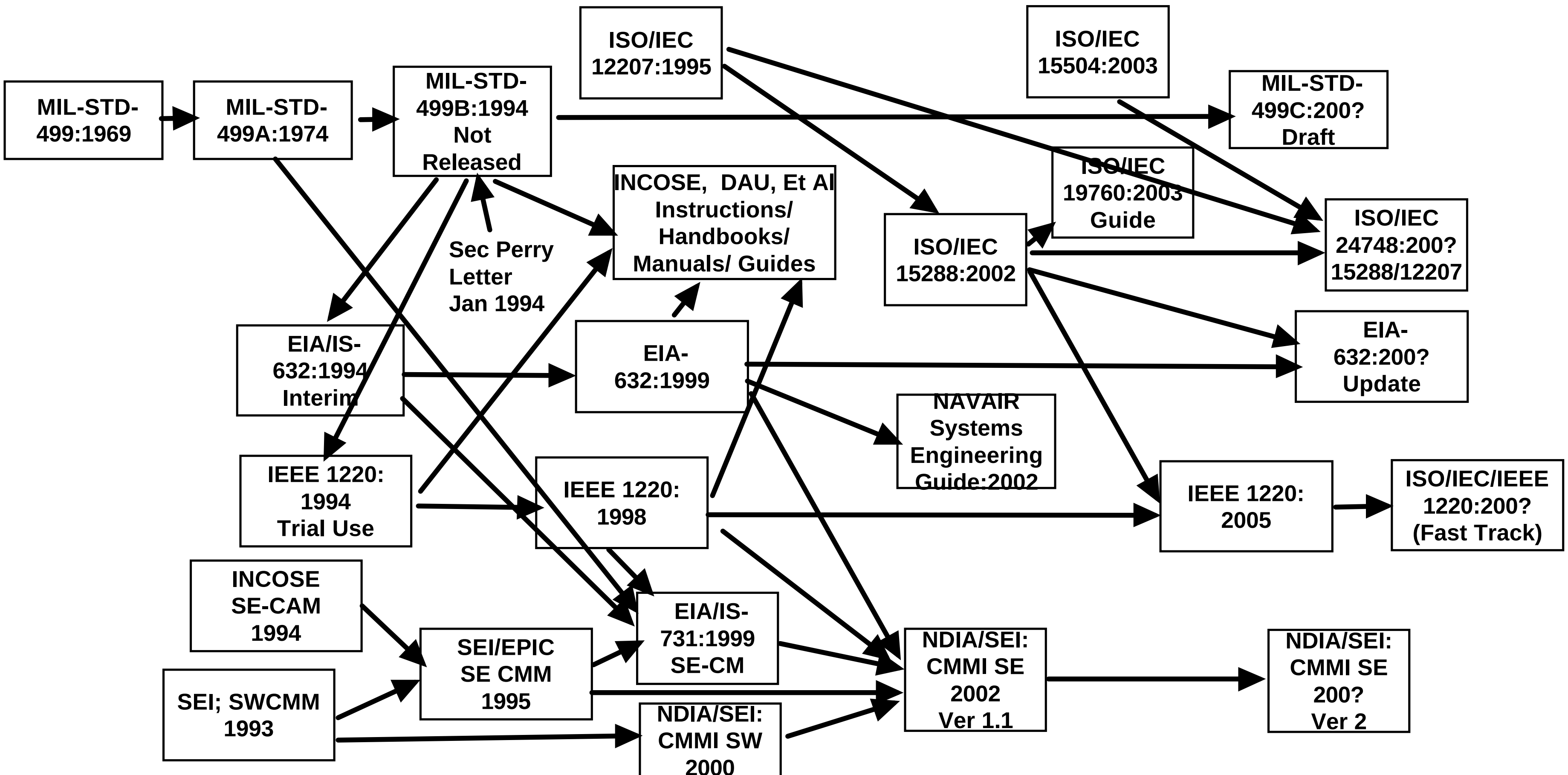
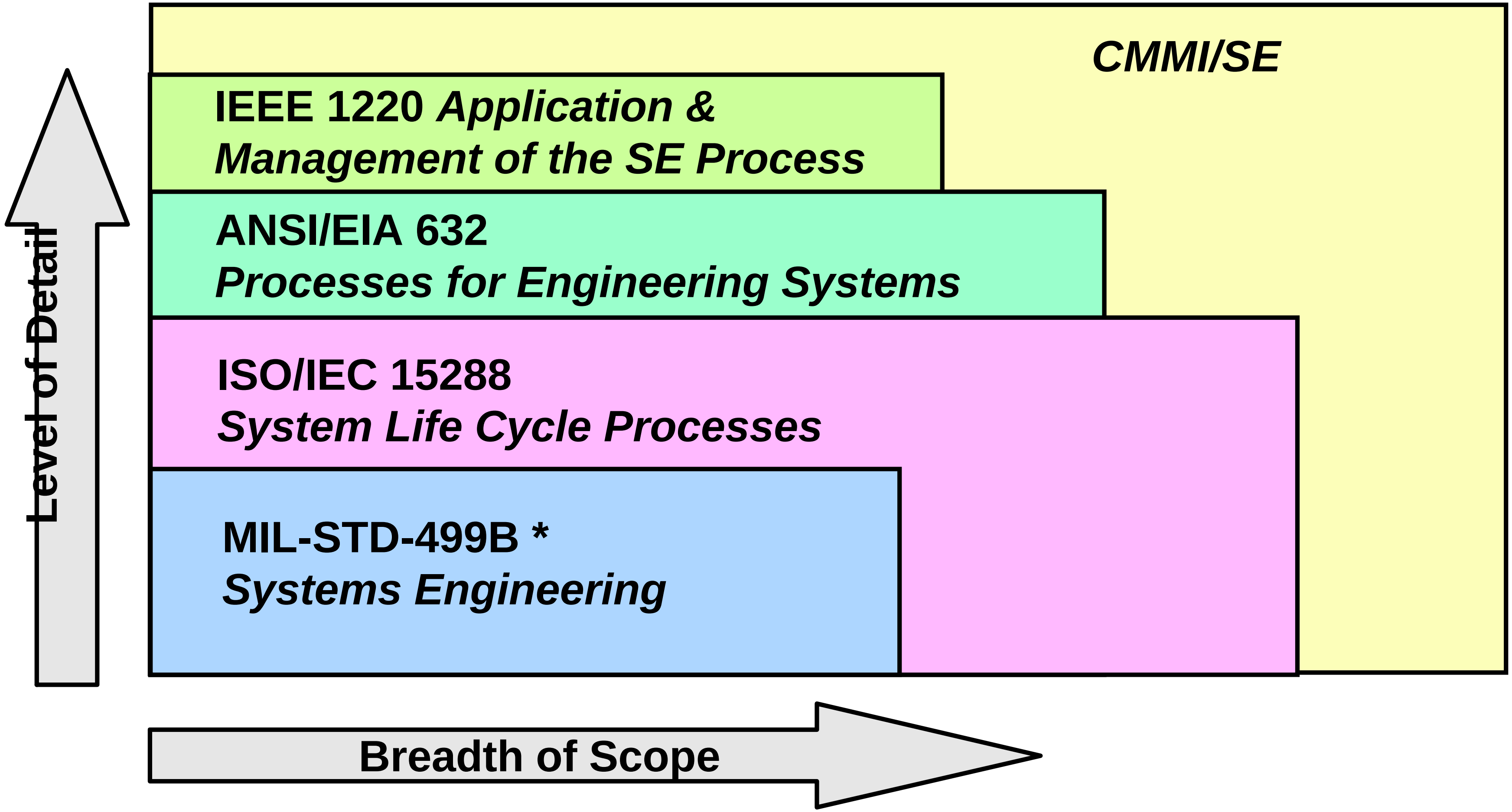
- But SE standard writers can't agree on what should be in a standard – Hence a quagmire!



Scope of SE Standards



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Ref: Lake **Briefing at February 2005 Ft Belvoir NASA Chief Engineer Workshop**

CMMI Recommended Maturation Path

	ML	CL1	CL2	CL3	CL4	CL5	Team Assessment
REQUIREMENTS MANAGEMENT	2						
MEASUREMENT AND ANALYSIS	2						
PROJECT MONITORING AND CONTROL	2	Maturity Level 2					
PROJECT PLANNING	2						
PROCESS AND PRODUCT QUALITY ASSURANCE	2						
SUPPLIER AGREEMENT MANAGEMENT	2						
CONFIGURATION MANAGEMENT	2						
DECISION ANALYSIS AND RESOLUTION	3						
PRODUCT INTEGRATION	3						
REQUIREMENTS DEVELOPMENT	3						
TECHNICAL SOLUTION	3	Maturity Level 3					
VALIDATION	3						
VERIFICATION	3						
ORGANIZATIONAL PROCESS DEFINITION	3						
ORGANIZATIONAL PROCESS FOCUS	3						
INTEGRATED PROJECT MANAGEMENT FOR IPPD	3						
RISK MANAGEMENT	3						
INTEGRATED SUPPLIER MANAGEMENT	3						
ORGANIZATIONAL TRAINING	3						
INTEGRATED TEAMING	3						
ORGANIZATIONAL ENVIRONMENT FOR INTEGRATION	3						
ORGANIZATIONAL PROCESS PERFORMANCE	4	Maturity Level 4					
QUANTITATIVE PROJECT MANAGEMENT	4						
ORGANIZATIONAL INNOVATION AND DEPLOYMENT	5	Maturity Level 5					
CAUSAL ANALYSIS AND RESOLUTION	5						

SE Gap Assessment indicates that CMMI Maturity Levels 2 and 3 should be developed in parallel for NASA

Systems Engineering Support to Program Management

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Program Management

- Planning
- Organizing
- Directing
- Monitoring
  - Maintaining insight or assessing
- Control

Common Areas

- Risk Mgt
- Config Mgt
- Performance
- Evaluation
- Mission Assurance

Systems Engineering

- Requirements & Functional Analysis and Allocation
- Design Synthesis
- Systems Analysis & Control (Balance)
- Integration &
- Verification

SE Gap Assessment also agrees with CMMI that Systems Engineering and Program Management must be integrated for NASA

Enterprise Systems versus Program Systems Engineering

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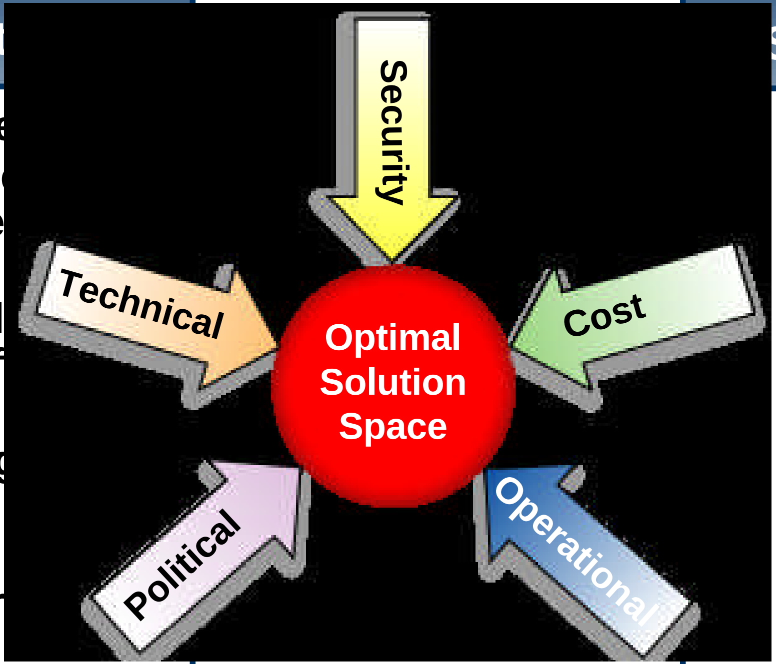
Single Systems Engineering (Stand Alone Syst

- End state well define
- Engineered and deve within a fixed budge and cost
- Well known schedul technical, and benef baseline
- Often replaces a "leg System
- Priority often
  - Technical/Secur
  - Operational
  - Cost
  - Political



Enterprise Systems Engineering System-of-Systems)

Dynamic end state

Systems-of-Systems evolves over time

Subject to annual budget revisions

Facilitates Senior Decision Makers

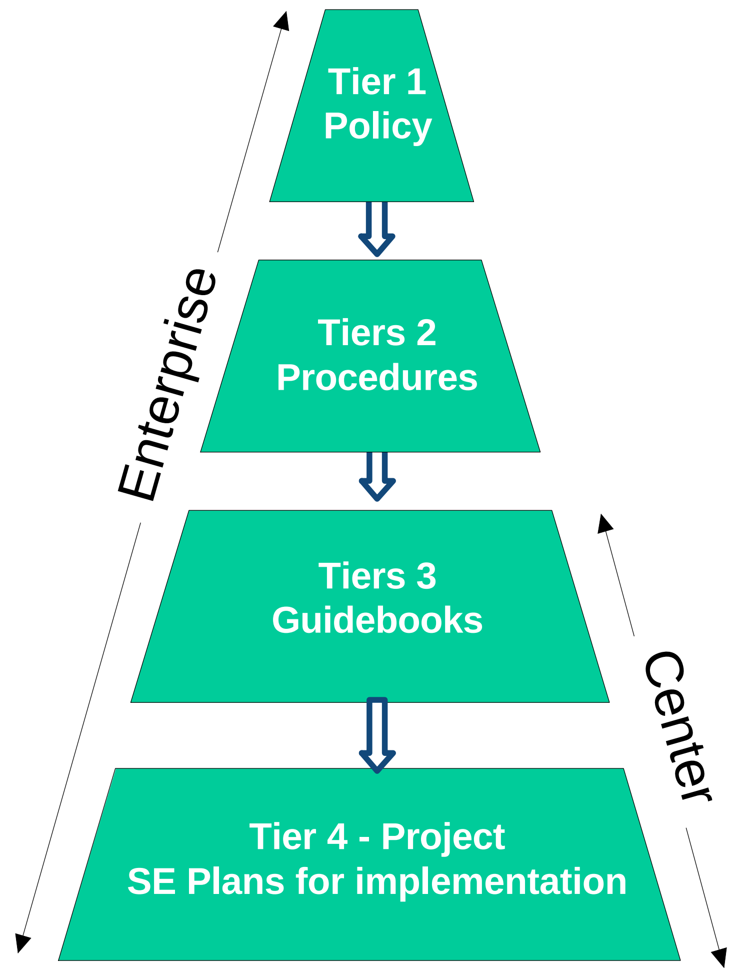
Priority often
- Political
- Cost
- Operational
- Security
- Technical

Competing Forces Addressed by Systems Engineering

Recommended NASA SE Process Development

- Tier 1: SE Agency Policy and Process Improvement Processes
  - **Process application policy**
  - **Architecture, Base and General Processes**
  - **Knowledge Management and Continuous Process Improvement**
- Tier 2: Process Area Procedures
  - **Specific standards and references identified**
  - **Process interfaces (HQ-Center, HQ-Contractor, Center-Contractor)**
  - **System of Systems integration**
  - **Can be tailored to specific directorate**
- Tier 3: Detailed Guidebooks

  Best practices of how to implement SE
  General tools and methods
- Tier 4: System Engineering Management Plans
  - **Technical program**
  - **Specific plans on SE implementation**
  - **Engineering specialty integration**
  - **Specific tools and methods selected**
  - **Organizational and contract interfaces defined**



System Engineering Processes Assessment and Vision

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Typical Today	5-Year Vision	10-year Vision	15-Year Vision
• national standard processes exist but in a quagmire of interfaces • NASA has a SE guideline (NASA SP-6105) that is only sporadically followed • no NASA-wide policy on systems engineering exists • NASA, DoD, and contractor teams use different processes and terminology	• A systems engineering policy, guidelines, and implementation strategies based on national standards and NASA/DoD/contractor best practices has been developed • Annual audits of NASA's systems engineering process model ensures best practices are used and distributed • A systems engineering certification program requiring continual education and training has been institutionalized • A knowledge management system for capturing and reuse of best practices and knowledge repository for cost, reliability, validated systems analyses and simulations, software, and hardware has been initiated • A completely digital product life-cycle management system for systems engineering and management for program/project control has been developed	• A collaborative / distributive advanced engineering environment for product life-cycle engineering and management has been developed based on system engineer and management processes for systems development and workforce training • Systems engineering, life-cycle cost, risk, and safety have been integrated for robust solutions of complex systems-of-systems development • All NASA centers have achieved the top level of systems engineering maturity • A certified (educated, trained, and experienced) systems engineering staff exists for engineering, management, and decision making • the organization interfaces and throughput is optimized through dynamic simulations	• an expert system for systems engineering exists to aid in the training and use of the validated advanced engineering environment for complex systems-of-systems developments • Knowledge management has revolutionized the startup of new programs with reuse of processes and tools • All decisions are based on validated simulations and virtual and surgical physical testing for performance, cost, safety, uncertainty, and risk (and politics!!) • a completed integrated international organization is optimized for the collaborative distributed environment

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Skills (Workforce)

Systems Engineering Architect/Specialist

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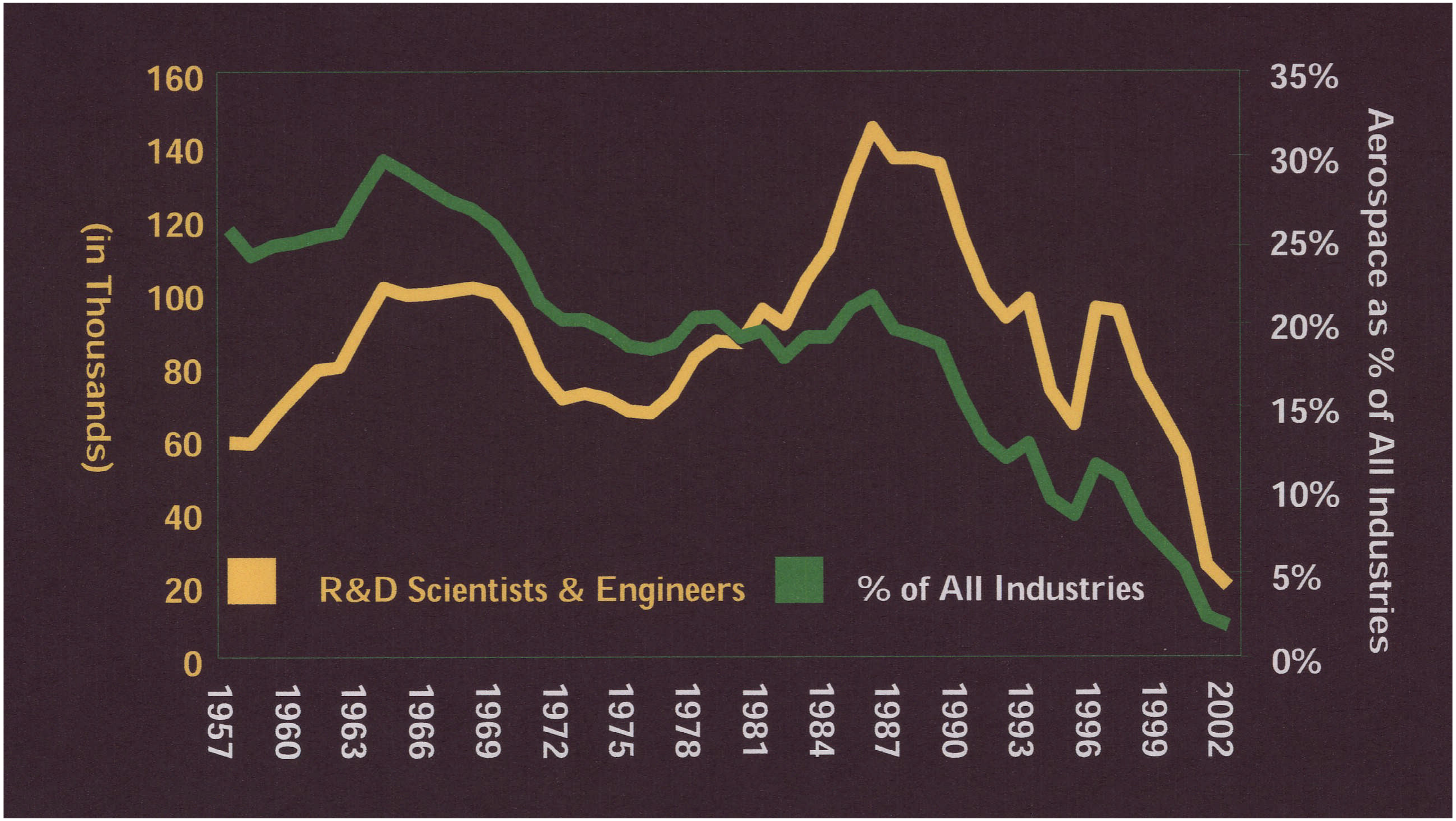
- Definition of a Systems Engineering Architect/Expert
  - Architect network centric and systems of systems
  - System Integrator
  - Drives next generation of mission solutions
- Attributes
  - Experienced technical leader
  - Experienced in working with the customer, understand their needs and customer value and to serve as the customer's primary technical interface
  - Expert in fundamentals – cost, schedule, risk, processes
  - System lifecycle experience from pre-proposal to logistics support
  - Understand hardware, software, mission and big picture
  - Solid interpersonal skills, verbal and written communications
- Lack of senior level experienced systems engineers/architects
  - Many self-proclaimed systems engineers
  - Exists both in industry and government

US R&D Scientists and Engineers



Degreed workforce is a shrinking pool.

The Resource Picture

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- Degreed workforce is a shrinking pool
  - Many graduates are not US citizens
  - Total engineering enrollments continue to decrease
- 20-30 year cycle between major system developments and 10 year development cycle
  - Lack of SE experience on large complex systems
  - Experienced SE engineers are retiring faster than being trained
- NASA systems engineering for human spaceflight has eroded and systems of systems is particularly acute (NRC 2004 NASA Systems Integration Study)
- Existing university / industry partnerships are not having enough impact
  - SE is not a standard discipline (EE, ChemE, ME etc.)
  - More penetration at undergraduate level
- Need new ways to attract and develop system engineers
  - Additional learning
  - On-the-job experience
  - Virtual simulation

NRO SE Certification Requirements

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Level	Experience	Training
I	**2 yrs. SE**	**SE-501 Acquisition Systems Engineering and** **SE-502 Designing Space Missions** ***or* 6 SE-related graduate credits** ***or* SPRDE Level II Certified**
II	**4 yrs. SE**	**Complete 4 from below:** **Requirements Development/Management** **Risk Management** **Measurement & Analysis** **Concept & Architecture Development** **Formal Decision Making** **Integration, Verification & Validation** ***or* 12 SE-related graduate credits or 6 after Level 1** ***or* SPRDE Level III Certified**
III	**7 yrs. SE**	**INCOSE Certification or** ***or* 18 total SE-related graduate credits or 6 after Level 2**

NASA needs to develop a SE certification program to develop systems engineering to meet future program requirements.

NASA SE Workforce Program

- Establish SE development policy including SE certification requirements for promotions
- Establish Government, industry, and academia SE education, training, and job experience partnerships
- Develop guidelines and process for SE graduated certification. Include integration with program management education and training
- Measure progress in SE workforce development and changes in program SE metrics

Workforce and Education Assessment and Vision

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<table>
<tr><th>Typical Today</th><th>5-Year Vision</th><th>10-year Vision</th><th>15-Year Vision</th></tr>
<tr>
<td>• "erosion of knowledge, experience and skills" in "systems engineering, project management discipline, cost, schedule management, and technology management". "particularly acute" for systems of systems integration. (NRC Systems Integration for Project Constellation, 2004)

• DOD has "essentially eliminated its systems engineering capability". (NRC, 2004)

• only a single capstone design course in undergraduate engineering

• courses taught in traditional classrooms

• some video and Web-based Courses</td>
<td>• A systems engineering certification program requiring continual education and training has been institutionalized

• just-in-time training via intelligent tutoring and advisory systems

• training support using standard NASA and enterprise product and process models

• focused training tuned to new opportunities and the best match with different employee skills and working styles</td>
<td>• Technological obsolescence of workforce virtually eliminated by a certified (educated, trained, and experienced) systems engineering staff for engineering, management, and decision making

• learning centers at each of NASA's Collaborative Engineering Environment facilities

• university use of collaborative, distributed- learning consortia

• practical experience of new engineers using validated system simulations

• technological obsolescence of workforce virtually eliminated</td>
<td>• Systems Engineering experience gained through simulation and on-the-job training

• Advanced Engineering Environment technologies and systems replicated at the university and used for maintaining a strong fundamental core course structure, with simultaneous links to the math and science departments and virtual links to industry and government laboratories

• national team teaching in engineering, math, science, management, and the humanities

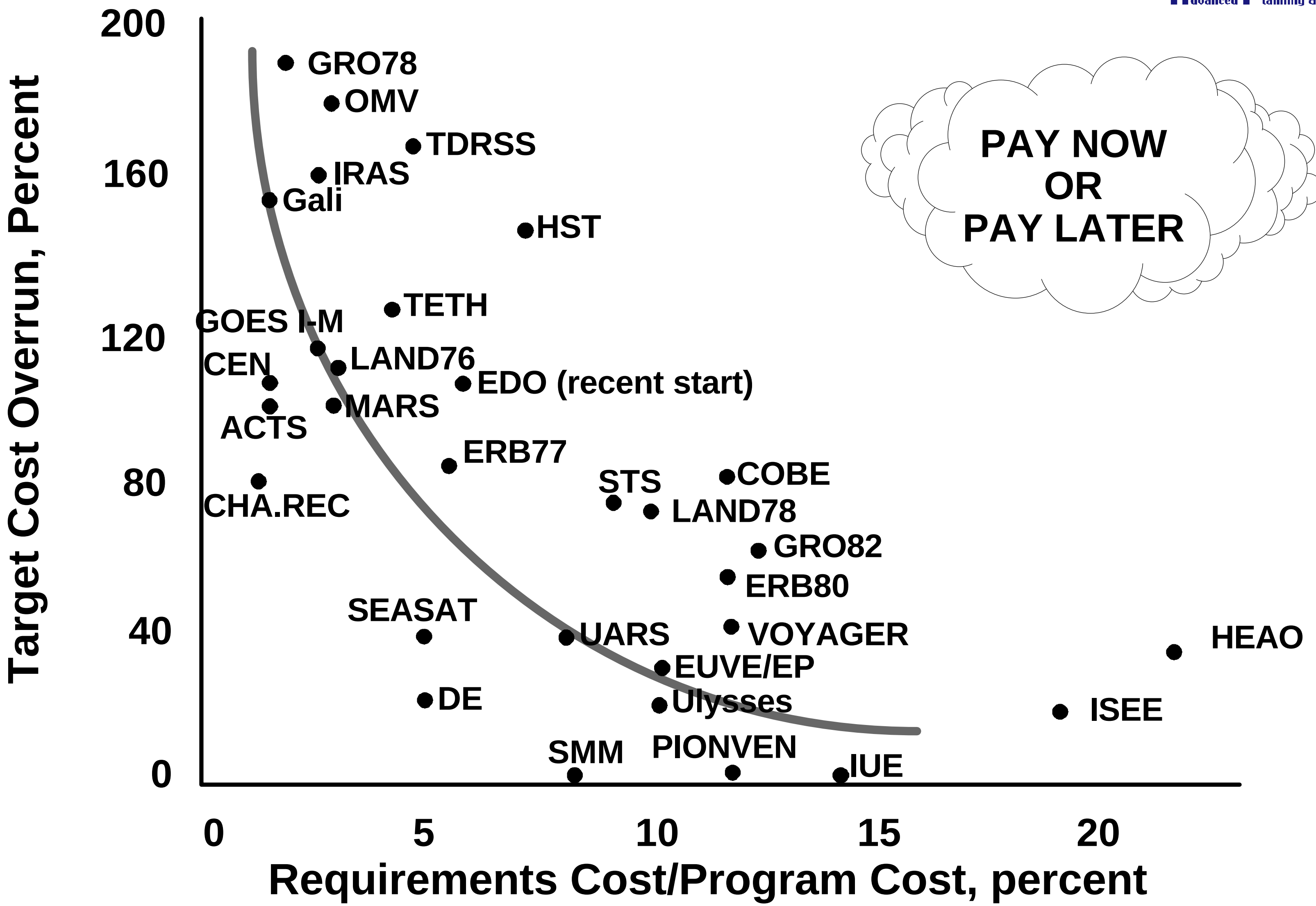
• personal learning experience emphasized —anytime, anywhere via an advanced Internet with high bandwidth

• just-in-time personal/virtual training and tutoring</td>
</tr>
</table>

Adopted from: "Design in the New Millennium: Advanced Engineering Environments", NRC 2000

Systems Engineering Tools and Methods

Effect of Requirements Definition Investment on Program Costs



The Systems Engineering Process
(Ref. ANSI 499)

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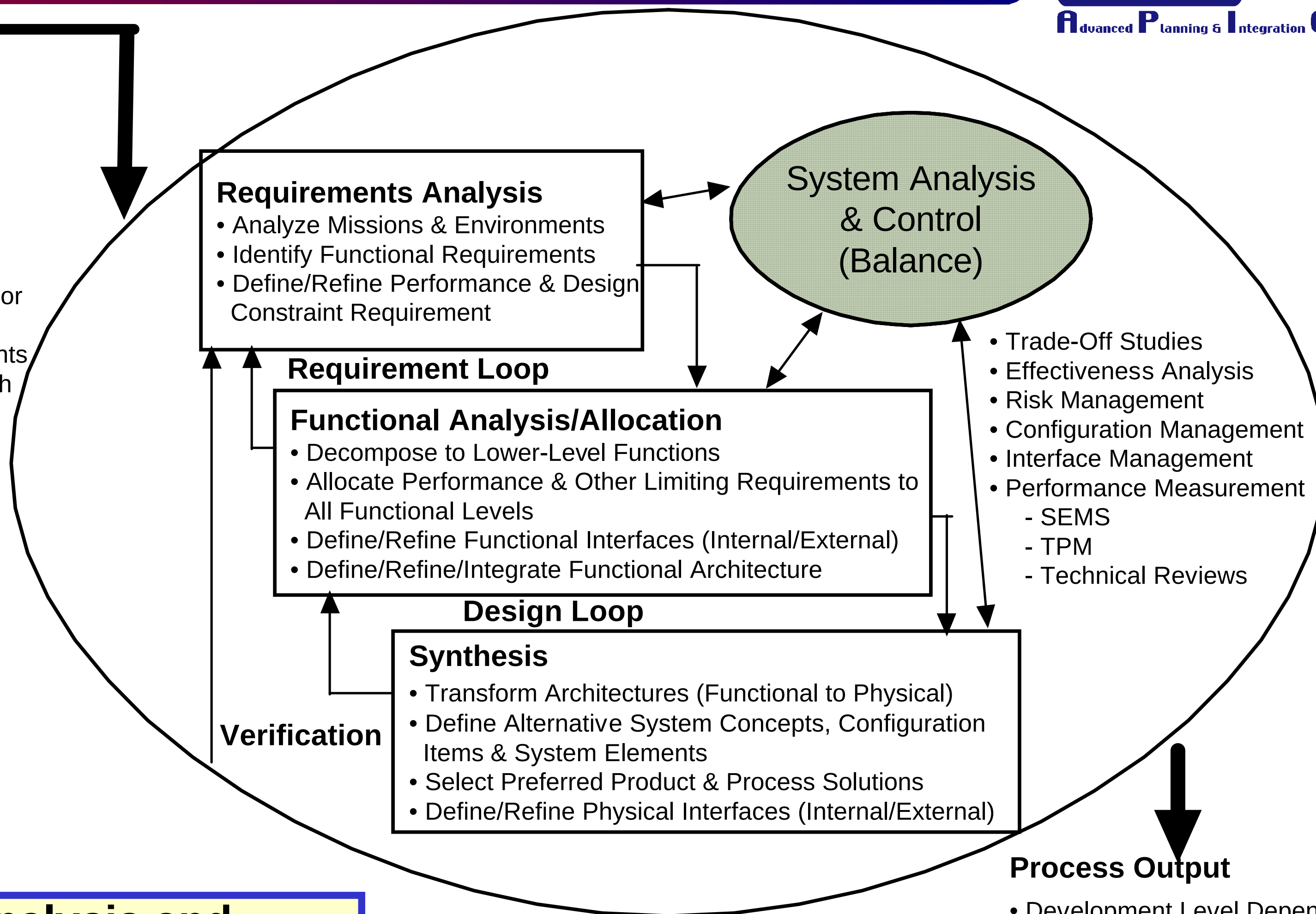
Process Input

- Customer Needs/Objectives/ Requirements
  - Missions
  - Measures of Effectiveness
  - Environments
  - Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards

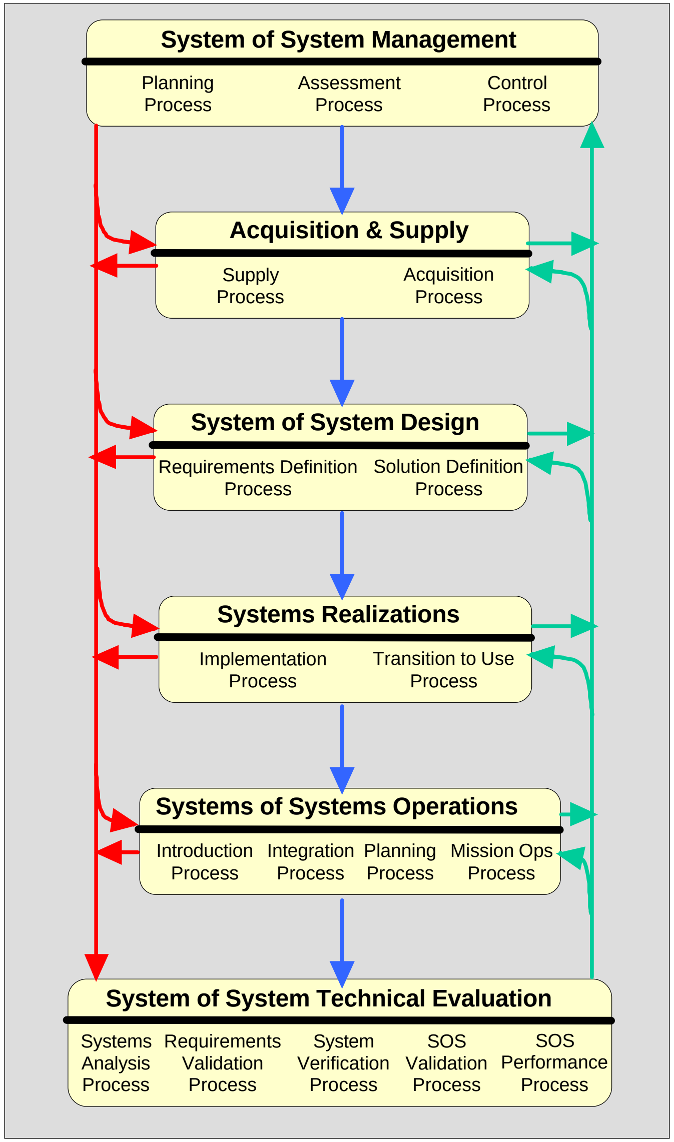


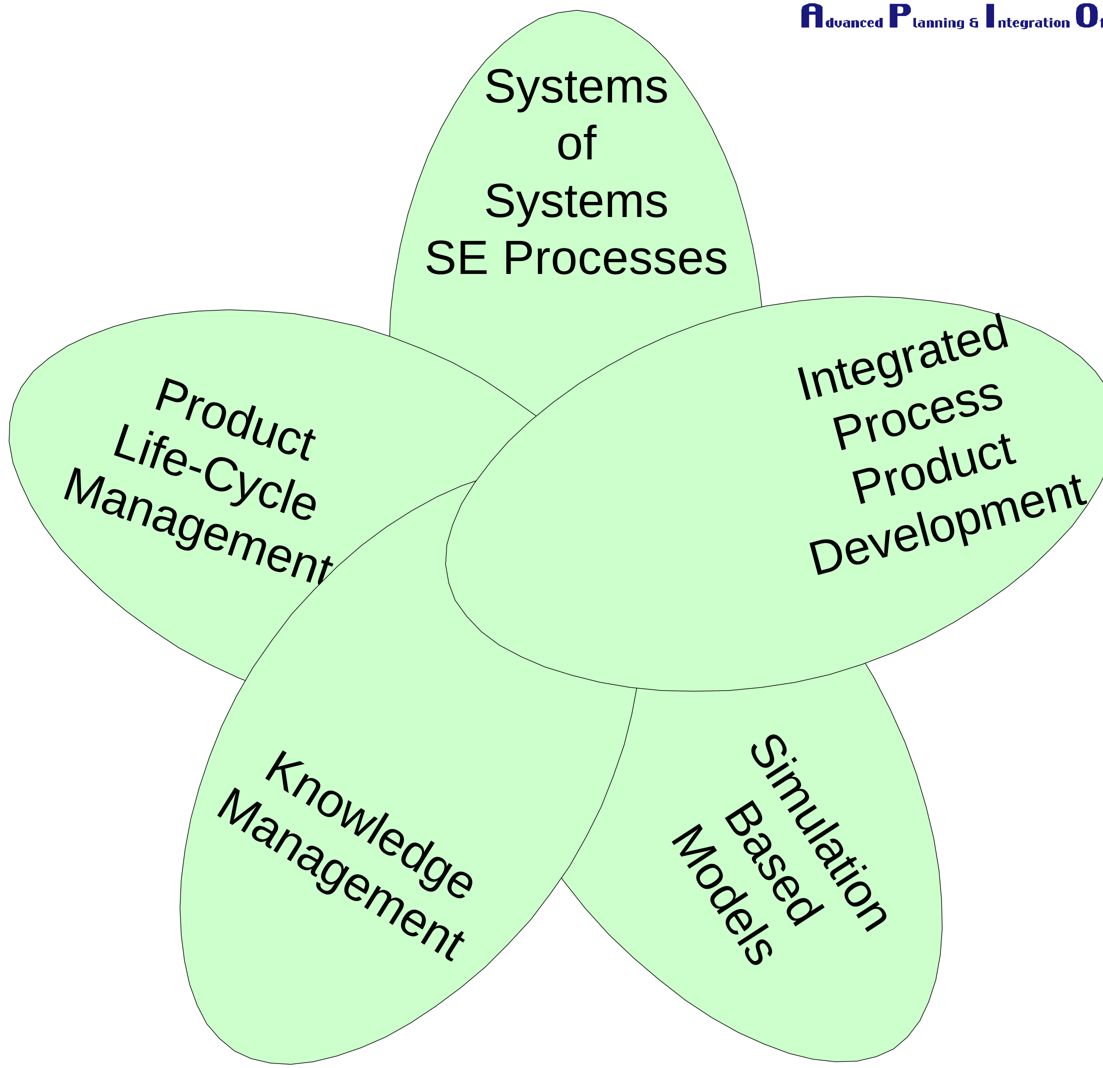
Process Output

- Development Level Dependant
  - Decision Data Base
  - System/Configuration Item Architecture
  - Specification & Baseline

Systems Analysis and Simulation drive the entire Systems Engineering Process

Integrated Systems Engineering and Life-Cycle Management





Product Life Cycle Engineering and Management Focus

Integrated Product Process Development

IPPD Defined: A management process that integrates all activities from product concept through production/field support, using a multi-functional team, to simultaneously optimize the product and its manufacturing and sustainment processes to meet cost and performance objectives. Its key tenets are as follows:

- **Customer Focus**
- **Concurrent Development of Products and Processes**
- **Early and Continuous Life Cycle Planning**
- **Maximize Flexibility for Optimization**
- **Use of Contractor Unique Approaches**
- **Encourage Robust Design and Improved Process Capability**
- **Event Driven Scheduling**
- **Multidisciplinary Teamwork**
- **Empowerment**
- **Seamless Management Tools**
- **Proactive Identification and Management of Risk**

Product Lifecycle Management (PLM)

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Stakeholders

Contractors

Product Life-Cycle Management

Systems Requirements

Configuration Items Specifications

CAD/CAM Standard Database

Change/Configuration Management

Virtual/Real System Models

V/R Production Models

V/R Verification Requirements and Management

V/R Validation Requirements and Management

Comprehensive Production and Quality History

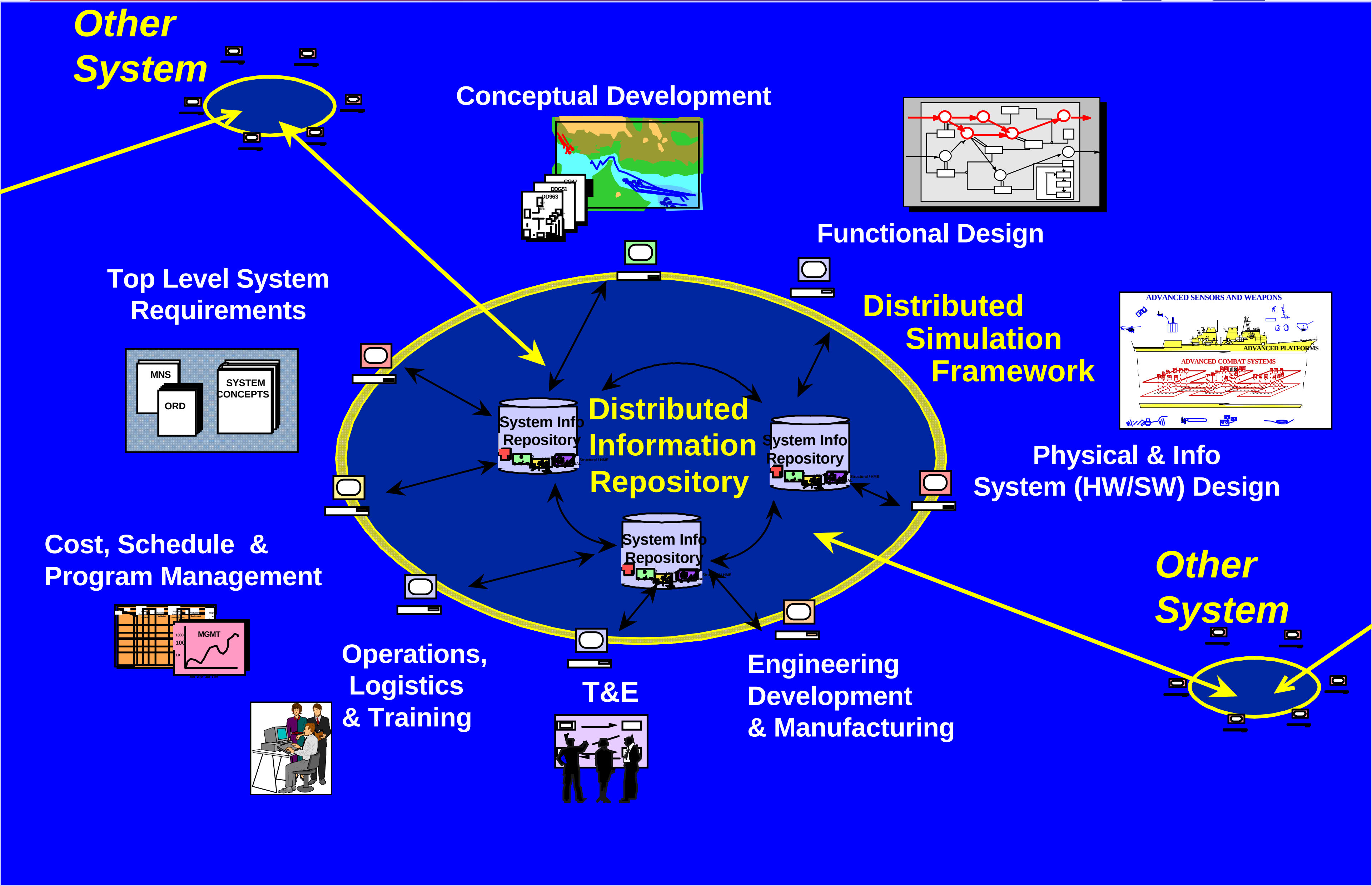
Resource Management

Supply Chain Management

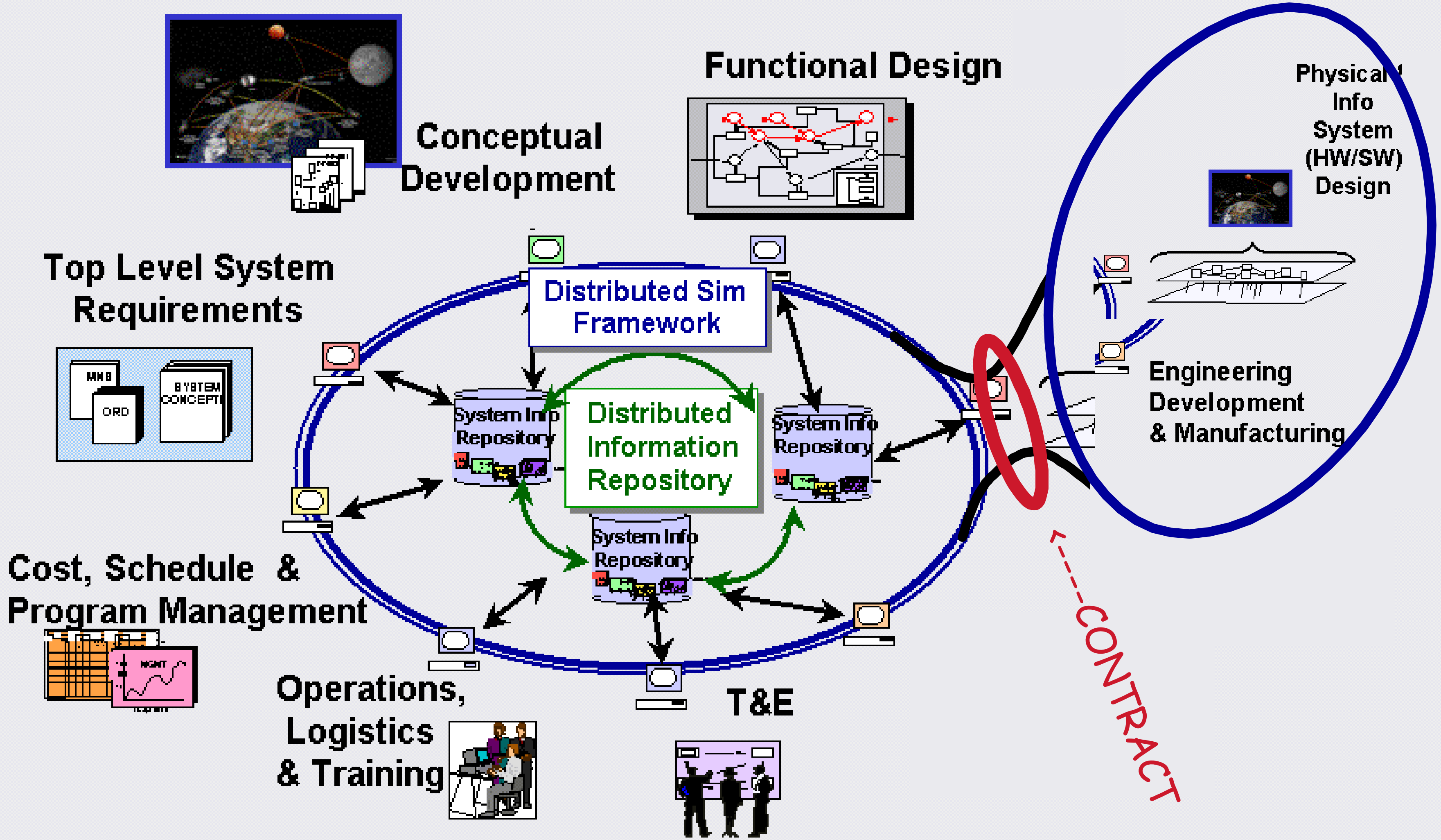
Management

Engineering

Simulation Based Systems Engineering



SBSE: The Challenge of Contracted Elements



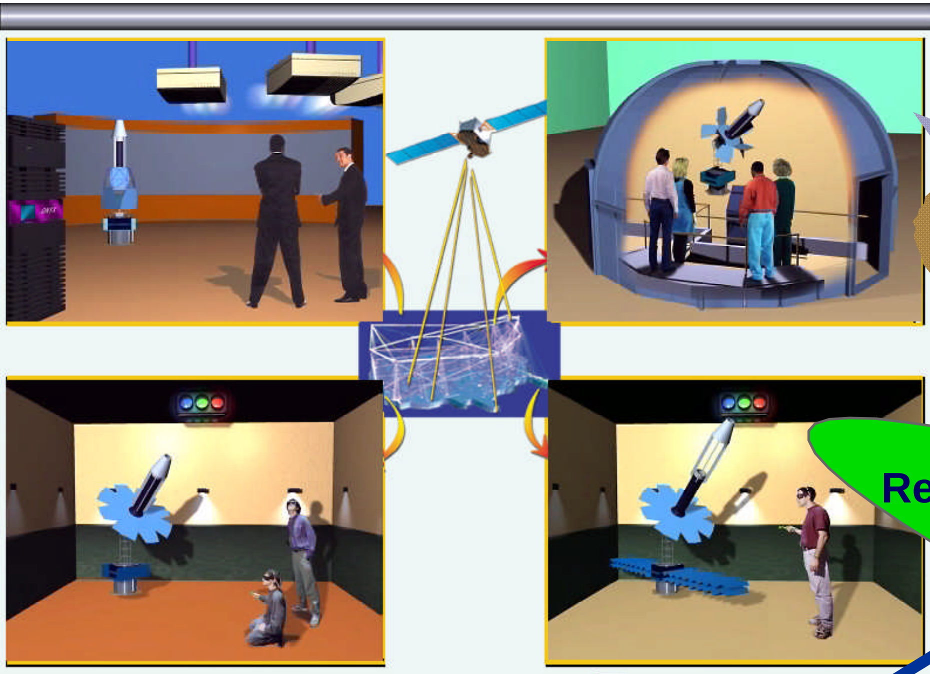
Fully Integrate Total NASA/Industry Systems Engineering and Management

Systems Engineering Tools and Gaps

Engineering Discipline Tools	- Mostly very good for detailed analysis; however needs standards for multidisciplinary integration for design and speed increases for optimization and uncertainty analyses.	
Specialty Engineering ("ilities") Tools	- Little confidence in prediction of causal relationships for reliability, maintainability, supportability, operability, availability, safety, etc.	
Life Cycle Cost	- NASA has continually underestimated the life-cycle cost (technology, development, production, operations, logistics). Needs causal models to assist engineering system and lifecycle design.	
Program/Project Management	- Many excellent tools available for cost, schedule, and configuration management; needs total integration including risk and engineering mitigation planning	
Product Life-cycle Management	- Many new COTS capabilities are being developed. Need to assess and select for NASA applications. Integration with simulation based SE modeling required. NASA wide and industry integration required.	

Critical Gap	
Significant Gap	
No or Minor Gap	

Systems Engineering/Robust Design



Requirements, Flowdown, Trades, Sensitivities, and Validation

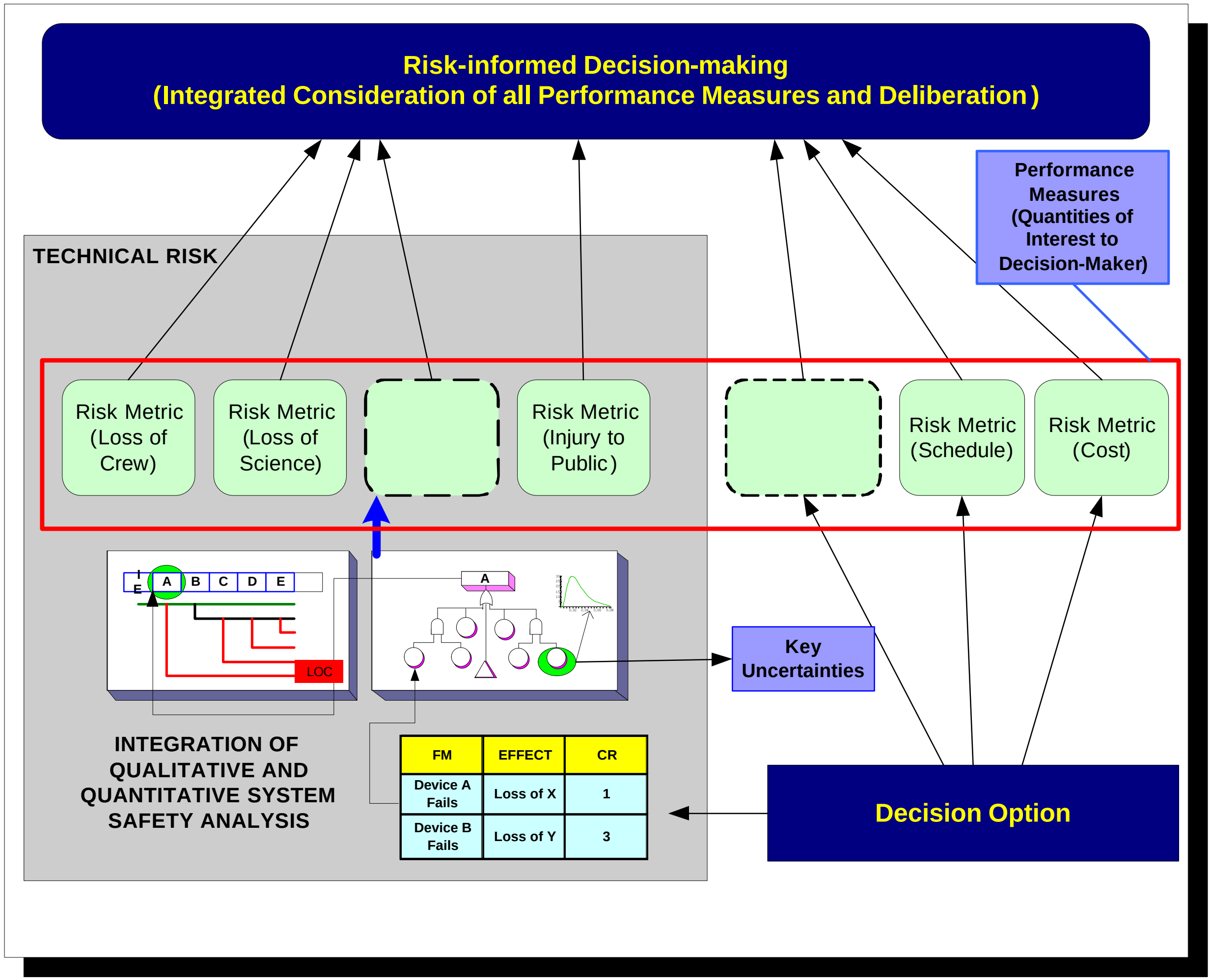
Advanced Tools and Processes

- High Fidelity Numerical Simulations
- Non-Traditional Methods
- Rapid Synthesis Methods
- Life Cycle Frameworks
- Life Cycle Cost Simulations
- Risk Simulations

Integrated Decision-Making

Integration of risk analysis with decision processes

Systems Engineering



Apollo Decision FOM Matrix (1962)

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	Performance	Probability of Success	Schedule	Safety	R&D Costs	Ops Costs	Growth Potential	Delivery Costs	Critical Development Problem Areas
EOR	15300	14.5 (w/spare)	Aug 1969	18.2	$6490 E6	$1240	12	$88.4 E6	a. Earth orbit rendezvous b. propellant transfer c. C-5 launch vehicle d. standard apollo capsule
LOR	12,600 5,000 LEM	19.1	Feb 1969	16.1 (CM) 22.0 (LEM)	$5840 E6	$620	10*	$77.4 E6*	a. lunar orbit rendezvous b. LEM and personnel transfer c. C-5 launch vehicle d. standard apollo capsule
C-5 Direct	9210	21.9	Oct 1968	16.7	$5690 E6	$510	12	$61.4 E6	a. high energy return b. light weight capsule c. C-5 launch vehicle
Nova Direct	15300	25.3	May 1970	18.0	$6160 E6	$630	15	$55.4 E6	a. Nova launch vehicle b. standard apollo capsule

Roadmap to Affordability Through Robust Design Simulation

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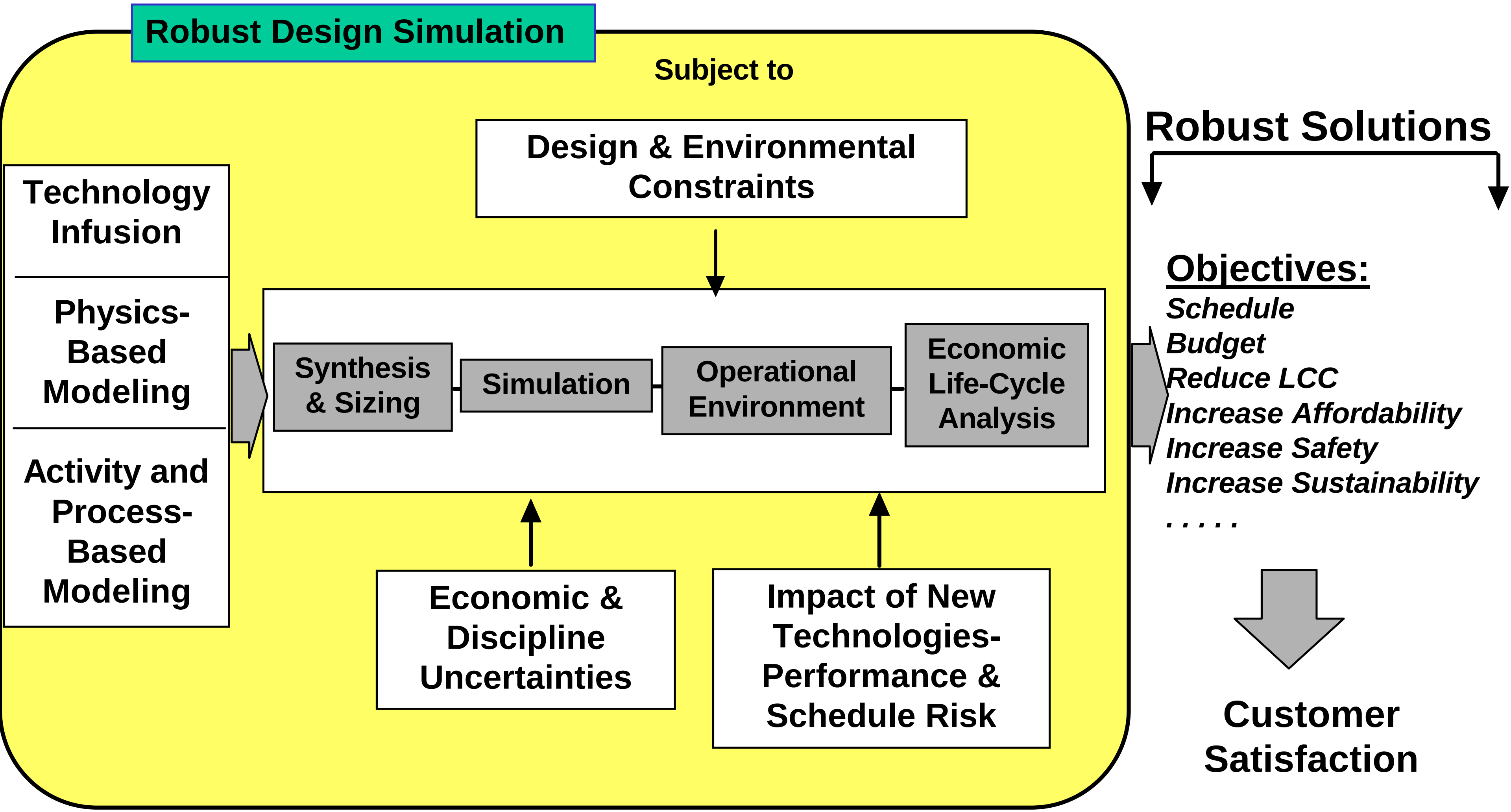
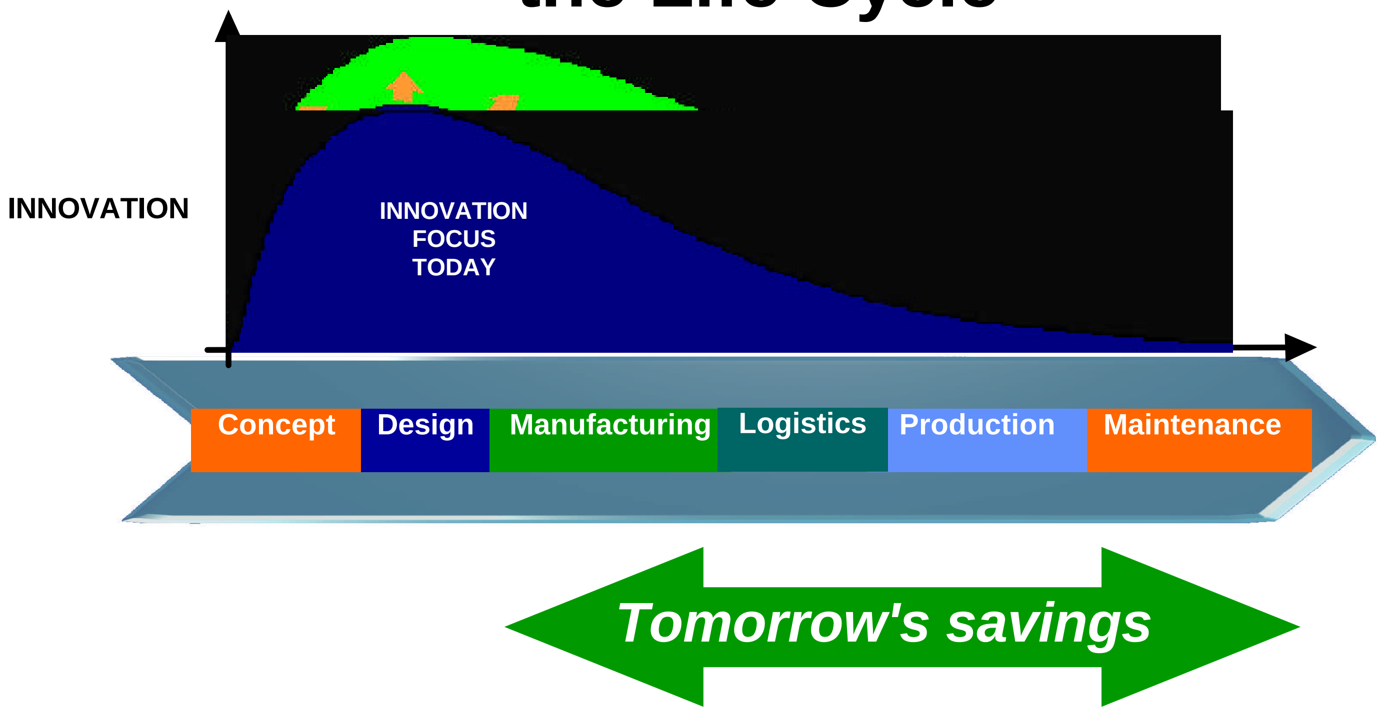
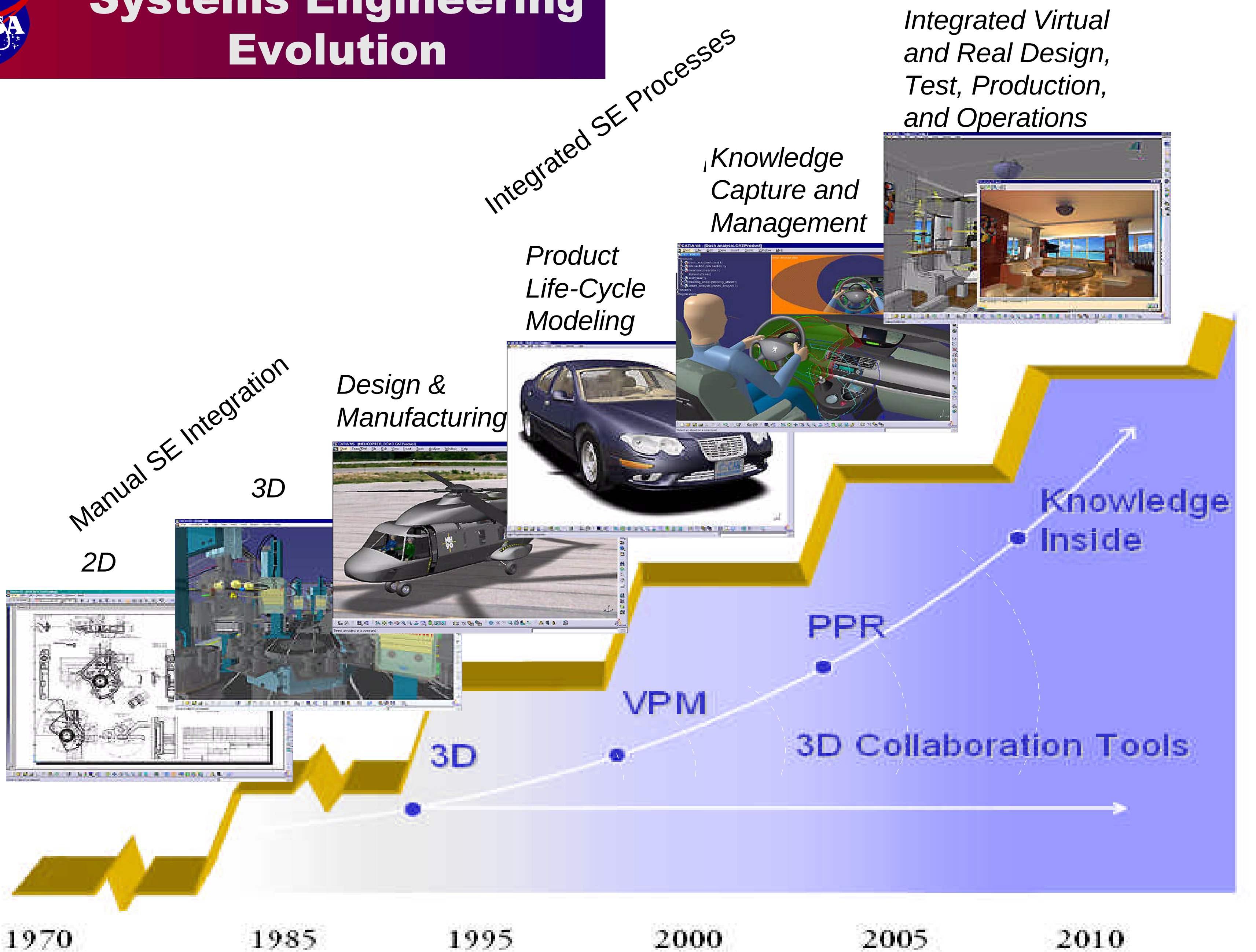


Innovation Focus Throughout the Life Cycle



Optimizing the re-use of Data and Corporate Knowledge

Systems Engineering Evolution



Rapid (Virtual and Real) Prototyping

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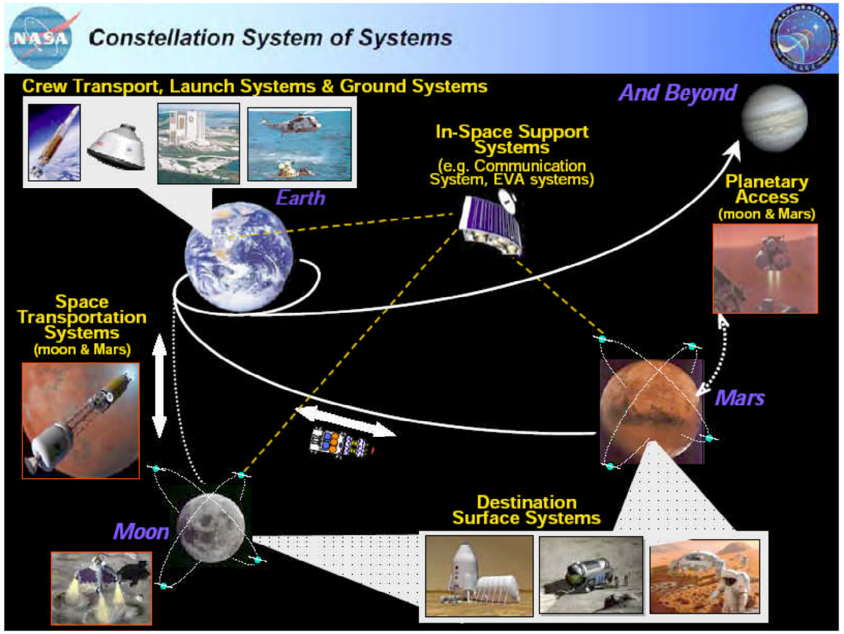
- Early Requirements Development
- Analysis of Alternatives
- Reconfigurable Designs
- Real/Virtual Integration
- Human/Machine Performance
- Safety, Reliability, Cost Trades
- Systems of System Integrated Performance and Decision Analysis



Rapid Validation of Virtual Models for Confident Decision Analysis

Define, Monitor, and Control the Physical World

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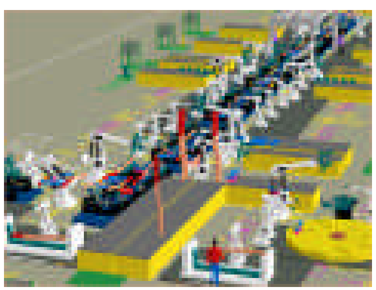
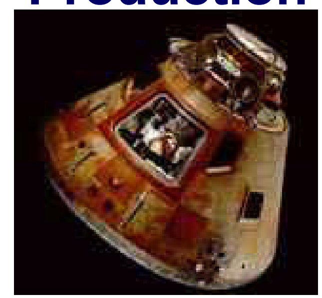
VIRTUAL | **PHYSICAL**

Product & Process Knowledge



INTELLECTUAL PROPERTY

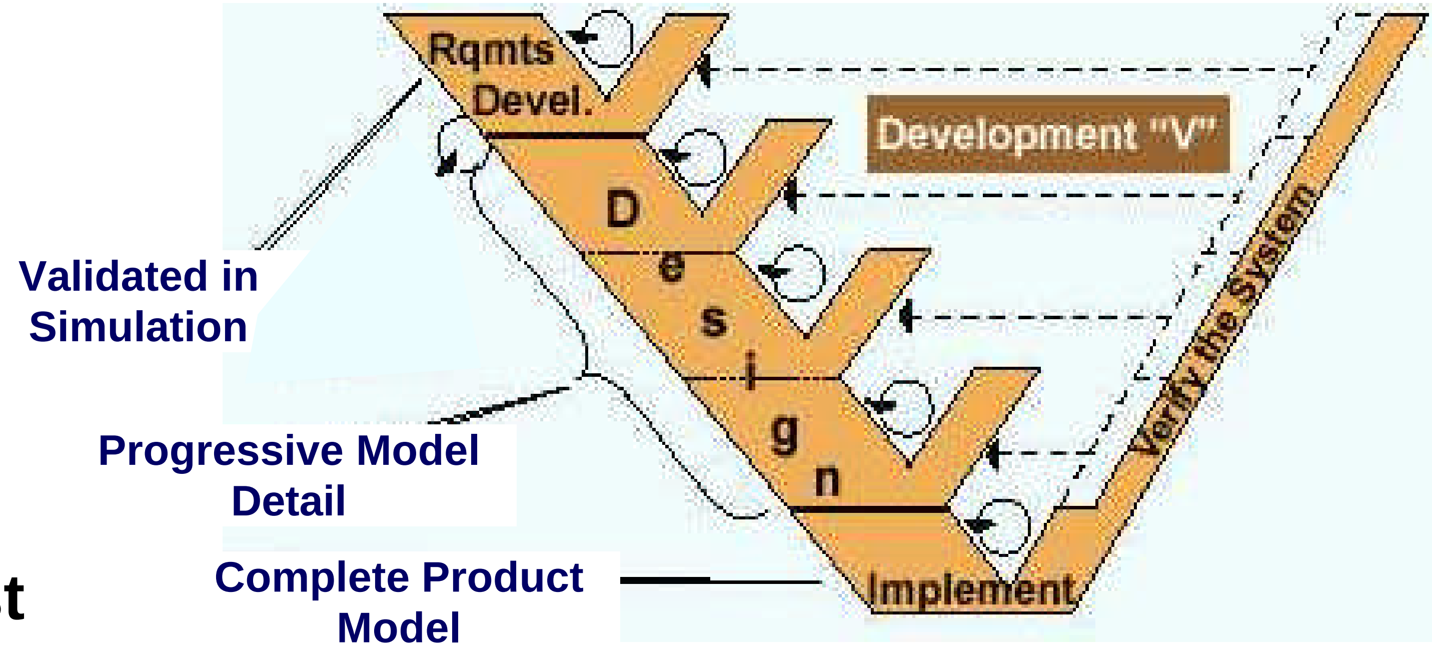
Production



REAL OPERATIONS

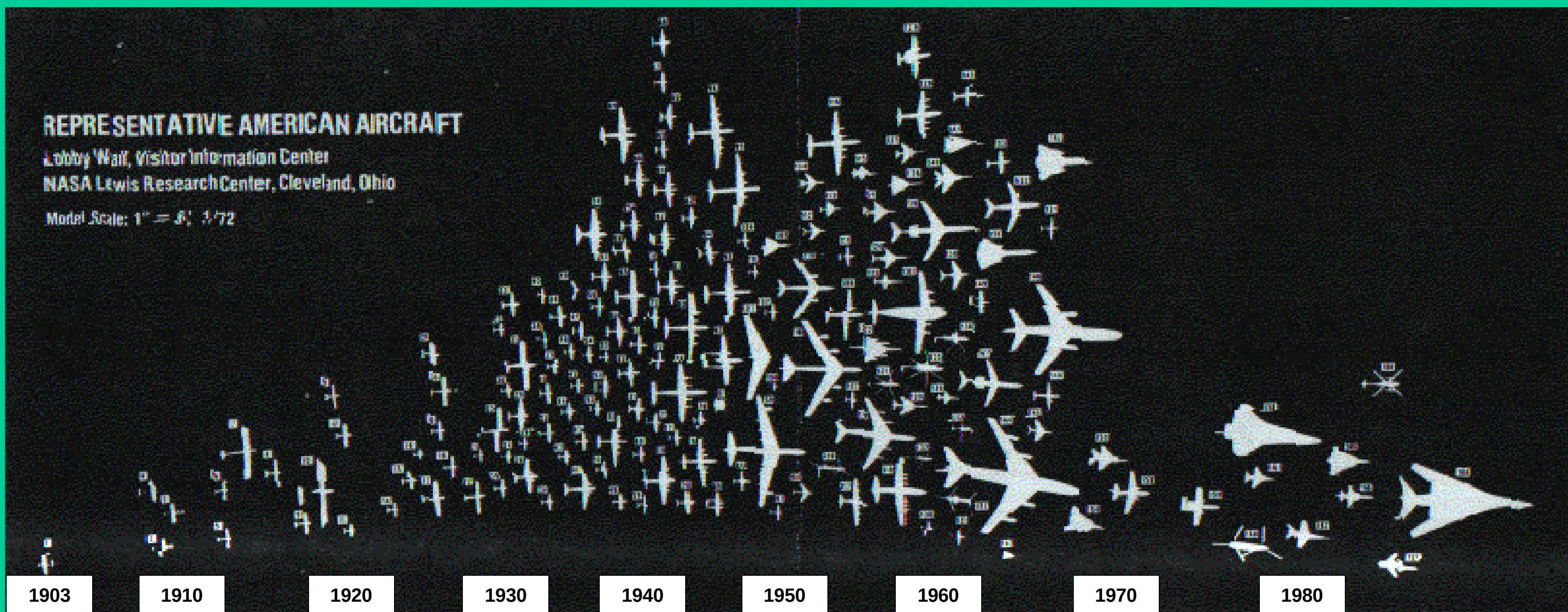
SBSE Integration with Systems Engineering

- **Design is Authored as Models**
- **Simulation Verifies the Design**
- **Physical Test Verifies the Simulation**



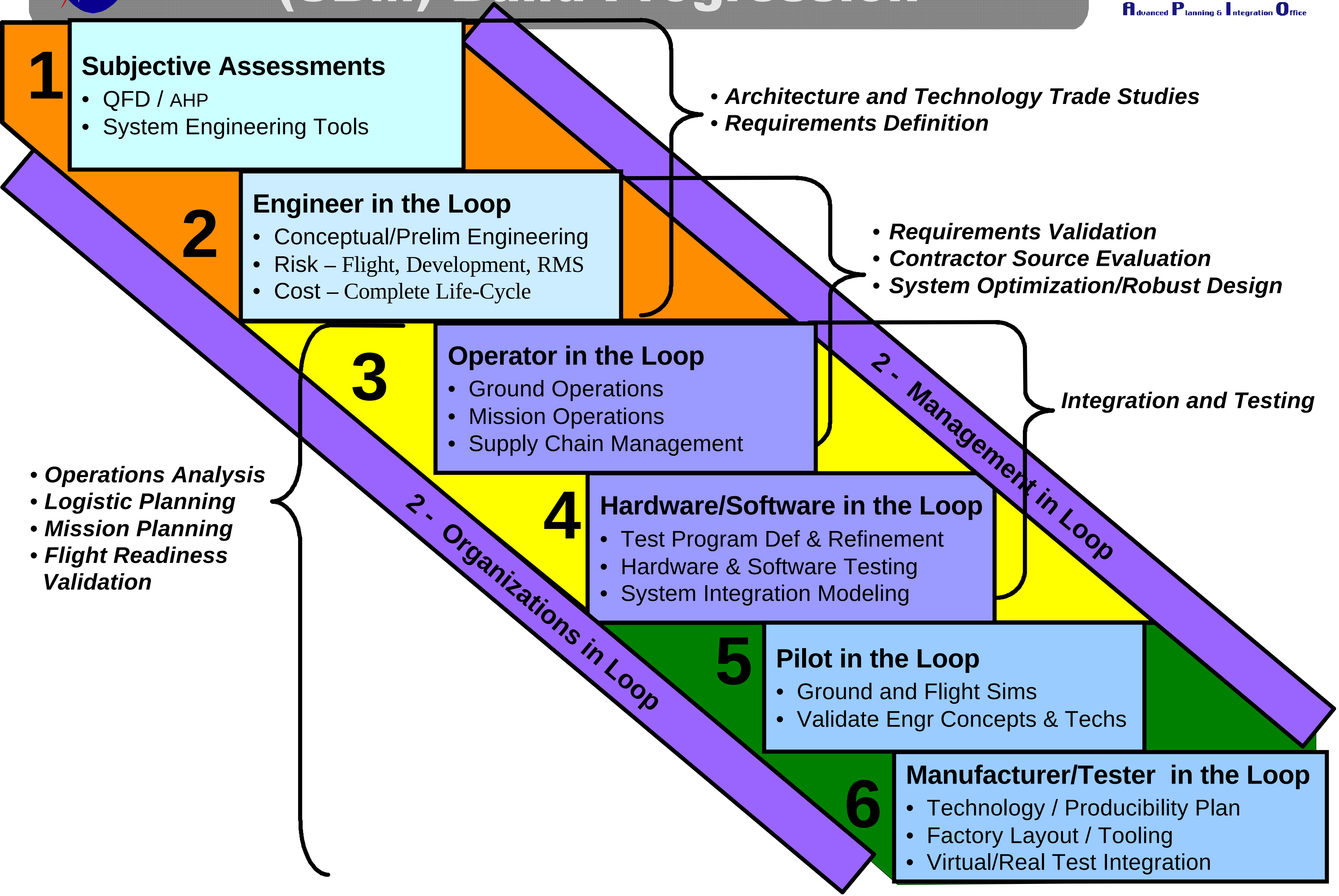
Better Decisions / Shorter Development Times

Virtual Simulation to Keep and Reuse Workforce Knowledge



Validated virtual simulation may compensate for lack of physical Systems Engineering experience.

Simulation Based Modeling (SBM) Build Progression



Collaboration/Distributive Environment

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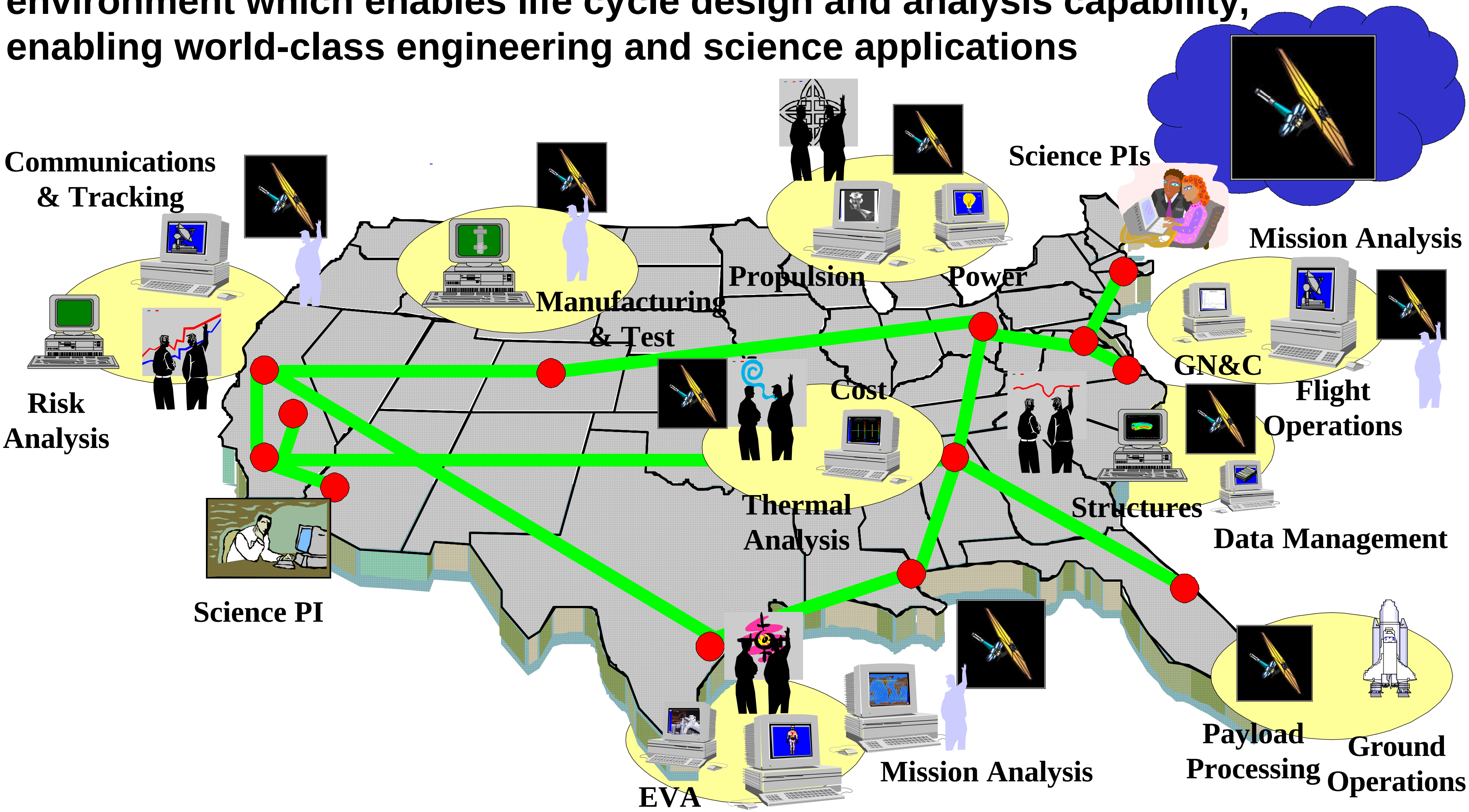
A geographically distributed, integrated, secure, collaborative environment which enables life cycle design and analysis capability, enabling world-class engineering and science applications



Modeling Management Structure
For STS Logistics, Management and Planning ~70%

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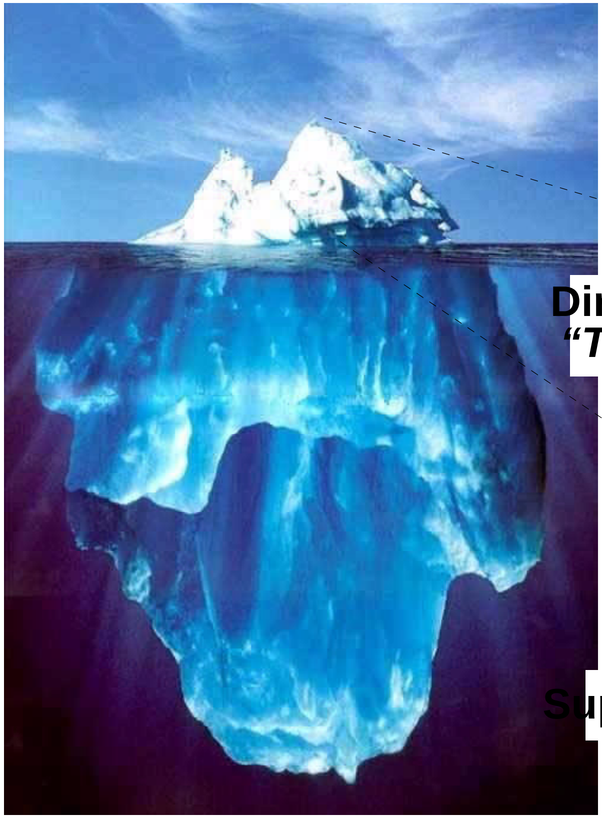

Direct (Visible) Wo
"Tip of the Iceberg

\+
Support (Hidden)

Recurring
Ops

STS Budget "Pyramid"
(FY 1994 Access to Space Study)

Generic Operations Function	Total $M FY94	*Total (%)*	
Elem. Receipt & Accept.	1.4	*0.0%*	~10%
Landing/Recovery	19.6	*0.6%*	
Veh Assy & Integ	27.1	*0.8%*	
Launch	51.5	*1.5%*	
Offline Payload/Crew	75.9	*2.3%*	
Turnaround	112.3	*3.3%*	
Vehicle Depot Maint.	237.5	*7.1%*	~20%
Traffic/Flight Control	199.4	*5.9%*	
Operations Support Infra	318.6	*9.5%*	
Concept-Uniq Logistics	842.7	*25.1%*	~70%
STS Ops Plan'g & Mgmnt	1477.4	*43.9%*	
Total ($M FY94)	**3363.4**	***100.0%***	
Percent	**100.0%**		

CM McCleskey/NASA KSC

Organizational Simulation

- Management and Organization integration is a major percentage of program costs
- Information flow, decision paths, and process graphs can be stochastically modeled for duration, human capital, and impact on total program costs.
- Currently, no organizational model has been developed to analyze NASA program organizational performance.
- Validated organizational simulations may have as much impact as system simulation and optimization

Systems Engineering Tools and Methods Assessment and Vision

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Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
1. Mission Requirements Analysis/Product System Strategy • high-level systems engineering analysis • stakeholder/mission requirements definition	• traditional systems engineering methods / non-standard application across NASA • little integration and reuse of engineering analyses • late trades of requirements versus system specs, performance, and cost	• establishment of NASA-wide policy and guidelines for systems engineering • integrated life-cycle analysis tools for system and requirements trades for acquisition	• integrated systems engineering and management systems for technical and programmatic risk • validated life-cycle simulation of all mission requirements • seamless transitioning of technical simulations to management and control simulation • systems of systems requirements are understood and validated	• all life-cycle engineering functions are seamlessly integrated for system design, development, manufacture, and operation • all mission and enterprise requirements can be traded with functional and physical models for the systems of systems environment • complete emersion of stakeholder in the design/requirements process
2. Product Specification • product strategy • voice of the customer • environmental and other regulatory requirements • planned product specification	• competitive comparisons • projections of future products • interviews and focus groups of customers and others • demonstrations • output is written documentation	• complete linkage of customer requirements, functional requirements, physical architecture, and operational requirements • virtual prototypes for specification validation • strategic decision models and analyses based on uncertainty and risk • product life-cycle model for management of complete digital product database	• knowledge base for construction of systems analyses for a proposal with a "selected" level risk • reliable specifications even for first-of-a-kind products • systems of systems impact of specifications are known	• reliable "batch of one" methods for unique products • product created on demand • ability to write in preferences and requests • maximum reuse of hardware, software, infrastructure, and knowledge for the enterprise

Adopted from: "Design in the New Millennium: Advanced Engineering Environments", NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
3. Concept Development • target setting • brainstorming on product and process alternatives • development of product and process concepts	• iterative, largely manual, bottom-up, non-optimized • expert opinion for concept initiation • rules of thumb • innovation relies on experienced practitioners	• integrated, predictive life-cycle cost and profitability models • optimization of shared resources • better models of cost and "ilities" for concept trades with customer requirements	• complete life-cycle optimizations trading safety, performance, life-cycle cost, technical/performance risk, and schedule • full automation of subsystem and component tracking and trade-offs • collaborative engineering environment for complete enterprise participation in engineering and management with contractors • virtual prototyping for manufacturing, integration, testing, ground and fight operations	**Steps 3, 4, and 5 combined** • concept is optimized to meet mission and enterprise requirements (hardware, software, and knowledge reuse known) - sensitivities, robustness, uncertainties are automatically generated for decision analysis • expert system generates alternatives • optimized, top-down concept development process • automatic analytical evaluation of all product and process attributes (including risk and uncertainty) • global collaborative engineering environment

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
4. Preliminary Product and Process Design • high-level definition of product and process designs • evaluation of product and process designs vs. targets • high-level system trade-offs	• iterative, largely manual, largely bottom-up, heuristic • derivations of existing designs • progressive definition • coarse definition, mostly manual from scratch • unequal levels of definition for new and reused parts • 20% of product and process attributes evaluated analytically using simplified models • reliance on physical prototypes	• rapid iteration of product and process design • object-oriented models scalable from macro to micro levels • single interoperable data set • automated process model creation • analytical evaluation of all attributes, including cost and producibility • multifunctional optimization	• some degree of iteration implied, but guided by optimization capability • analytical evaluation of all attributes, 200 to 300 times faster than current methods • integrated; single data source • full automation of subsystem and component tracking and trade-offs • virtual manufacturing	• single-pass product and process design and concurrent evaluation with multifunction optimization and automatic cascade to next lower level of design • automated generation of details about component and subsystem design and manufacturing details from high-level descriptions and desired attributes • single product life-cycle data source

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
5. Refinement and Verification of Detailed Product and Process Designs • development of designs for components, subsystems, and manufacturing processes • geometry creation • prediction and evaluation of all product and process attributes • tracking and trade-offs of subsystems and components	• detailed process and product definition mostly manual and from scratch • limited reuse of design geometries for new parts • analytical evaluation of one-third of product and process attributes using detailed models • some model sharing • reliance on physical prototypes • attribute prediction and evaluation partially automated, but not integrated with design evolution	• distributed, collaborative processes within NASA • physical prototypes essentially eliminated • real-time sharing of design information	• automatic configuration control and tracking of system and processes • distributed, collaborative processes (NASA and contractors) • design advisors • minimal, “surgical” testing • no late trade-offs and no errors	• automatic verification of the system and processes generated within the NASA advanced engineering environment • immersive design and evaluation environment from the total NASA/ contractor engineers, managers, and decision makers • international distributed, collaborative processes

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
6. System Prototype Development • experimental refinement of product attributes that do not meet targets	• analytical evaluation required for more than half of all product attributes • real and virtual prototypes available for form, fit, and function demonstrations and tests	• integrated database for development of rapid prototypes • virtual prototypes becoming the norm for NASA	• complete virtual prototyping of system, systems, manufacturing, integration, tests, and operations	• validated virtual models - limited experiments required
7. Production, Testing, Certification, and Delivery	• virtual shop floor modeled • discrete event optimized production flow • on-line statistical process control	• product life-cycle model used to integrate production with resources, supply chain, workforce, and management • products with 100% quality—getting it right the first time	• all production hardware, software, infrastructure, workforce, and processes developed and tested virtually • complete supply chain modeled and integrated with production • off-line robust design • lean, agile manufacturing • design for manufacturing: fewer parts, more compatibility, and easier assembly processes	• complete integrated virtual environment for supply chain, production, integration, verification, and validation • virtual design and manufacturing process with zero defects • only minor facility reconfigurations required for single product runs

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
8. Operation, Support, Decommissioning, and Disposal	• sequential, historically based modeling approach • a lot of manual operations	• consideration of remanufacturing in design • limited autonomous systems • simulation models based on operational processes • improved automation of support activities • supply chain modeled for impacts on design	• autonomous systems • operations driven supply chain fully modeled and managed • design for easy repair • design for disassembly • design for reuse and remanufacture	• autonomous systems • self-healing • self-disassembly • self-disposal

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Capability 15.1 Systems Engineering Roadmap

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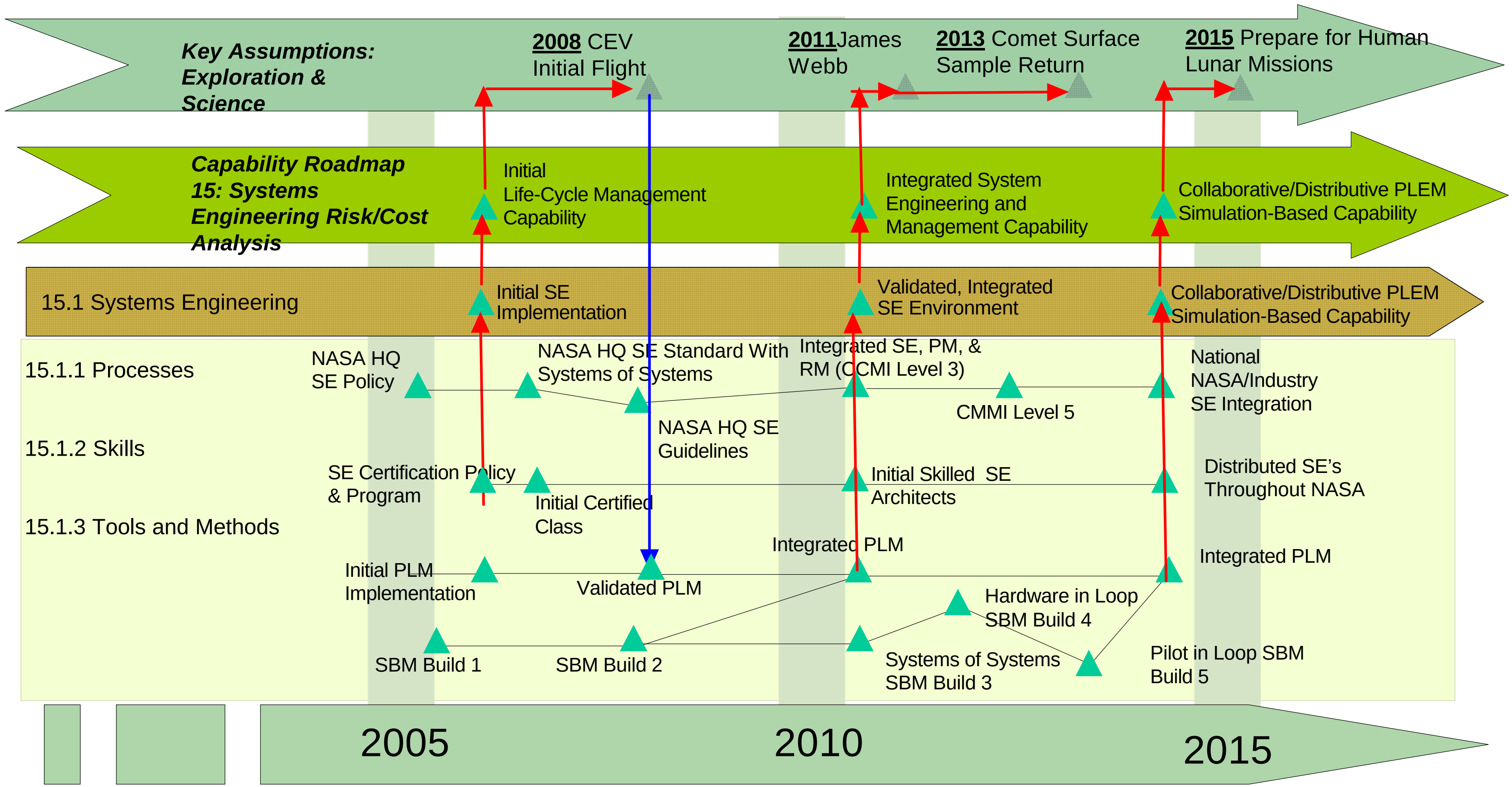


Major Decision

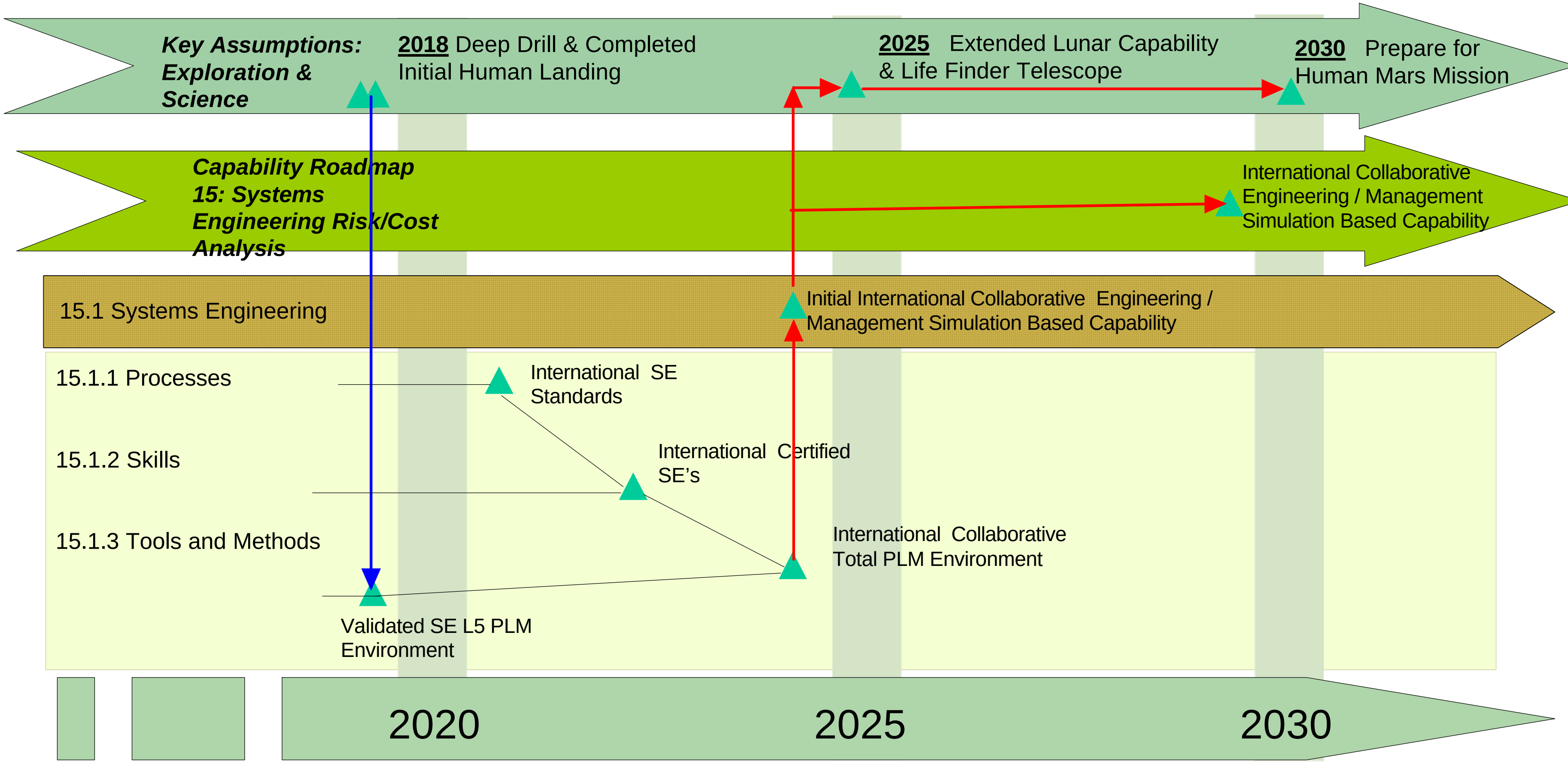
Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Capability 15.1 Systems Engineering Roadmap



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Summary

- Systems Engineering in NASA needs to be improved for large complex systems of systems projects
- Standard system engineering policy needs to be developed at the Agency level for guidance to Centers
- The training and education of systems engineering needs to be institutionalized
- Advanced Engineering Environment can greatly enhance program execution, workforce training, and search for innovation and improved science

Capability - 15.2 Life Cycle Cost

Presenter:

Dr. David Bearden

What is a Life Cycle Cost (LCC)?

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- An integrated, process-centered, and disciplined approach to life cycle management of projects provides real and tangible benefits to all project stakeholders.
- A LCC estimate includes total cost of ownership over the system life cycle, all project feasibility, project definition, system definition, preliminary and final design, fabrication and integration, deployment, operations and disposal efforts.
- A LCC estimate provides an exhaustive and structured accounting of all resources necessary to identify all cost elements including development, deployment, operation and support and disposal costs.

*** Definitions provided by the NASA Cost Estimation Handbook, 2004**

Benefits of the Life Cycle Cost

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- “Ensure cost realism and accuracy”
  - The President’s Commission
- Improve confidence in selection process
  - Enables better budgeting
- Predict cost impact of change
- Limit potential for significant overruns
  - Increases mission success
- Gauge economic impact of decisions

Cost Team Process

- **Evaluated current Capability Readiness Level (CRL) of cost discipline, at the lowest cost team WBS level**
  - **Cost Analysts at NASA HQ, MSFC, JPL, SAIC and The Aerospace Corporation evaluated the readiness level and importance of the current State of the Practice**
  - **Scored Robotic Spacecraft and Human Space Flight separately**
- **Interviewed Agency cost estimating leaders for current status / initiatives**
- **Identified remaining near-term gaps after implementation of current initiatives**
  - **Recommended additional measures for near-term**
- **Envisioned ideal state for cost estimating**
  - **Five and twenty year horizons**

Current State-of-the-Practice for Life Cycle Cost

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- Tools
  - Primarily system level parametric models with broad application
  - Medium fidelity models for development and operations
  - Low fidelity requirements (Physics) based models for instruments
  - High fidelity component models limited in application
  - Immature technology development capability
  - Scattered, sparsely-populated databases deployed across centers and industry
  - Databases with limited content, pre full-cost accounting and not normalized
- Skills
  - Limited formal cost training in academia
  - Limited career path
- Process
  - Program costs rolled up from several models
  - Costs validated through comparison of bottom's up to parametric (top down)
  - Periodic intersection of cost estimation with project development
  - Immature linkage to Schedule Analysis
  - Minimal understanding of relationship of LCC to mission risk and safety

Maturity Level – State of the Practice for 15.2 Life Cycle Cost

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Robototic Spacecraft			
Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation			
Development			
Production			
Operations			

Human Spaceflight			
Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation			
Development			
Production			
Operations			

Critical Gap	
Significant Gap	
No or Minor Gap	

Results indicate a strong need for Technology Maturation Cost Estimation Capabilities

Observations on Maturity

- Capability ratings trended higher for Robotic Spacecraft than Human Spaceflight primarily because of better data availability (function of more recent, relevant missions)

- Capability ratings for Technology maturation cost estimating low in all areas

- Production and Development estimating limited by data available in Human Spaceflight area

- Operations cost estimating readiness low due to less mature tools and processes and availability of fewer estimators

Requirements/Assumptions for Life Cycle Cost

- Missions Driving Requirements
  - Primarily driven by ESMD
    - Prometheus
    - Crew Exploration Vehicle
    - Human Exploration of Moon/Mars
  - Large SMD Projects
    - James Webb Space Telescope
  - Scale of large ESMD and SMD projects increases budgetary impact of overruns, poor estimation, and requirements creep

- Additional reports that drive capability
  - 2004 Aldridge Commission Recommendations On NASA Cost Estimating
  - 2004 GAO Report on NASA Cost Estimating
  - NPR 7120.5C
  - 2004 NASA Cost Estimating Handbook

Elements of LCC Roadmap

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- Tools
  - One NASA Cost Engineering (ONCE) Database
  - Technology Development Estimation Capability
  - Integrated Cost, Risk, & Schedule Models
  - Integrated Life Cycle Models with Improved Operations Models
  - Requirements (Physics) based Models
  - Economic Modeling
- Skills
  - Continuous Development
  - Formal Academic Education
- Process
  - CADRe (Cost Analysis Data Requirement) feeds data to ONCE
  - CCRM (Continuous Cost Risk Management)
  - Standard WBS
  - CAIG-like (Cost Analysis Improvement Group) implementation

Cost Estimating 5 Year Vision

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"Enable a more agile cost estimating capability that interacts effectively with the project management function"

- **Improved models**
  - **Representative Initiative: Integrated Life Cycle parametric system level models**
  - **Remaining Gap: Importance of accurate cost information justifies more investment to build higher fidelity integrated models**

- **Improved database**
  - **Representative Initiative: CADRe -> ONCE**
  - **Remaining Gap: Better coordination and cooperation by data owners (data sharing by centers/ involved parties), data availability is a long-term problem**

- **Enhanced process to enable use of LCC estimating as an input to the project management function**
  - **Representative Initiative: CCRM**
  - **Remaining Gap: CCRM implementation will be challenging**

Capability 15.2 Life Cycle Cost Roadmap

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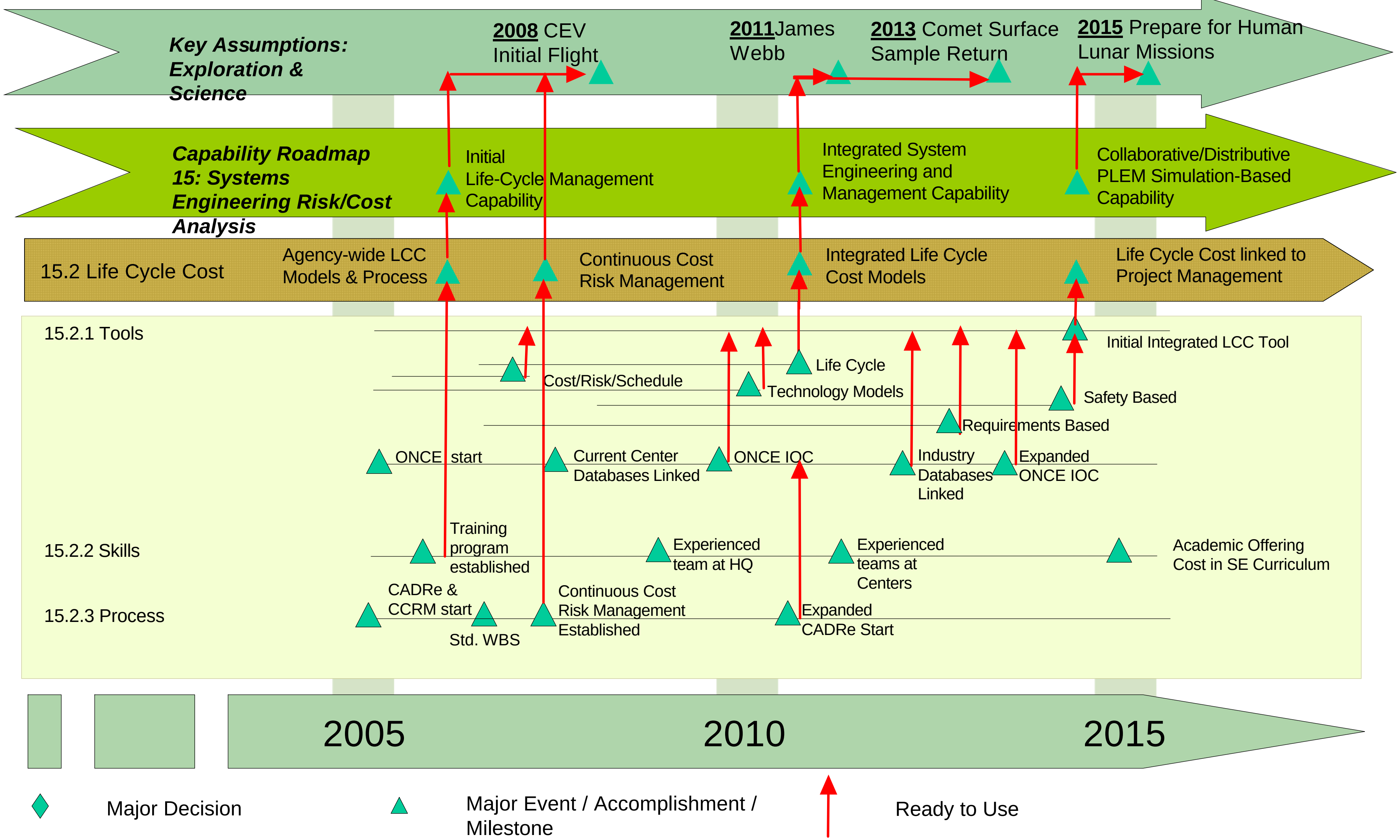

Cost Estimating 20 Year Vision

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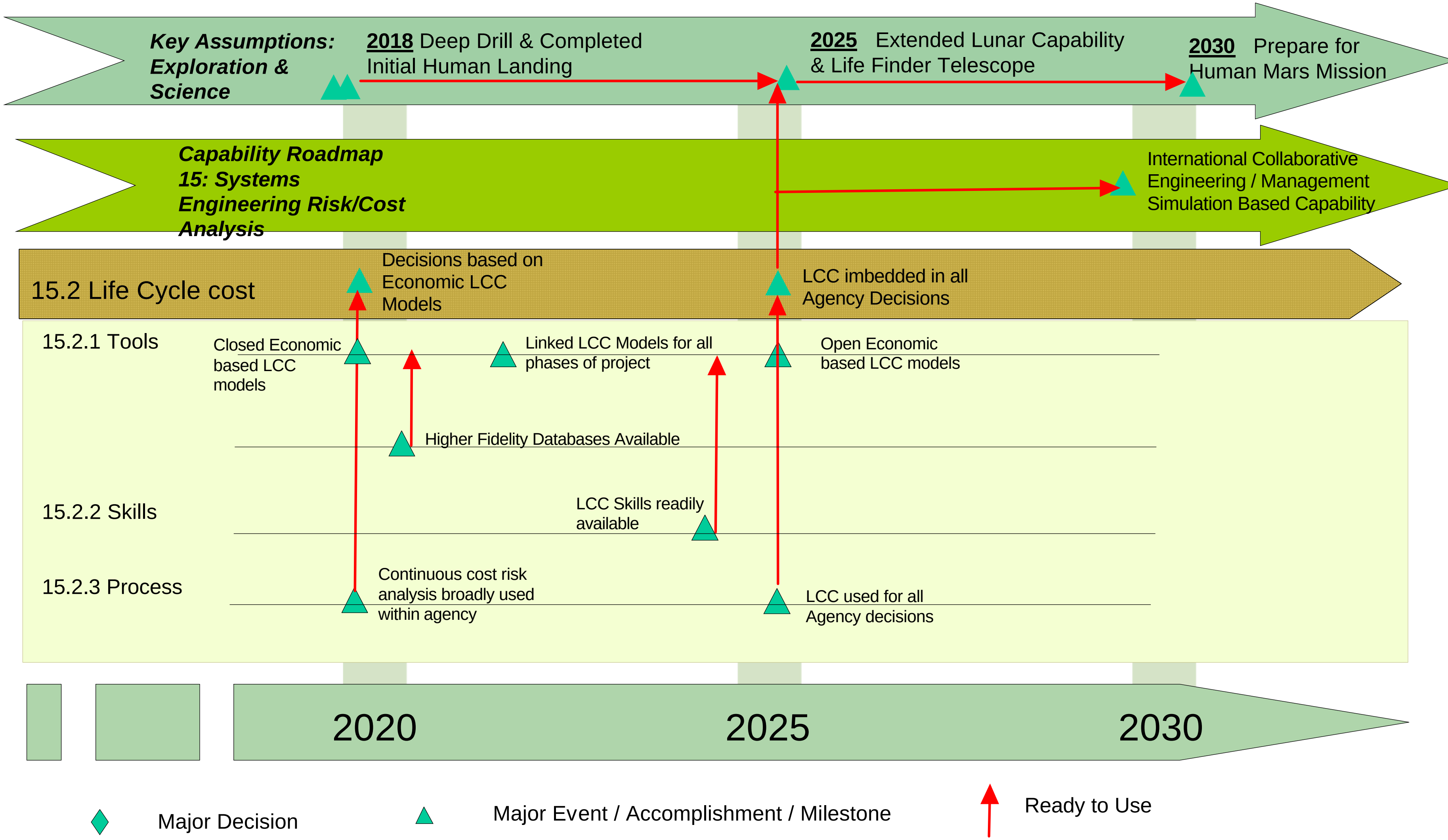
"Create a cost estimating capability that simulates the economic system and interacts seamlessly with management and systems engineering throughout the project"

- **Understand the whole economic system and simulate to understand the effects of design and programmatic decisions have at the industry base level**
  - **Model not only design solution, but economic business case for industry**

- **Link the project management and systems engineering process with cost analysis**
  - **Simulate technology changes, process changes, etc.**

- **Improve tools and databases to allow for high-fidelity analysis**
  - **Cost as a function of safety, risk, schedule, and technology**

Capability 15.2 Life Cycle Cost Roadmap



Life Cycle Cost Goals

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Capability	Year 5	Year 10	Year 25
MODELS			
Cost Accuracy	30%	20%	10%
Schedule Accuracy	30%	20%	10%
DATABASE			
% of Programs w/ Complete CADRe	50%	90%	100%
SKILLS			
% Staff w/ Formal Training within NASA	50%	75%	90%
PROCESS			
% Programs implementing full CCRM process	30%	60%	90%

Summary

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- Evaluated current capability of cost estimation discipline
- Envisioned ideal future state for cost estimating
- Performed gap analysis taking into account current initiatives
- Developed roadmap from current state-of-practice to envisioned state

Capability – 15.3 Risk Management

Presenter:

Theodore Hammer

Capability – Risk Management

Advanced Planning & Integration Office

- **Risk Management identifies potential problem areas early enough to allow development and implementation of mitigation strategies. This includes contingency planning, descope approaches, and qualitative and quantitative assessments. As complexity of systems grows the importance of risk analysis increases in managing cost, schedule and mission success.**
- **The Risk Management sub-element needs to be thoroughly integrated with other aspects of systems engineering**
- **Risk management includes tools, processes, and skills**

Key Points/Benefits

- **Risk Management most effective when integrated with program/project and technical management**
- **Gaps exist within the present risk management state of the practice**
- **First End State targets elimination of existing gaps**
- **End States target delivery of capabilities five years prior to a milestone**
- **Regular evaluation critical**
- **A formal integrated risk management capability benefits implementation of highly complex systems by**
  - Enabling cost effective implementation and problem avoidance
  - Increasing probability of mission success
  - Reducing programmatic problems (e.g., cost and schedule)

Current State-of-the-Practice for Risk Management Within NASA

- Risk Management policy and requirements exist
- Conduct annual NASA Risk Management conference
- Risk Management planning widely used
- Assessments are highly qualitative
- Quantitative assessments using such tools as PRA are limited
- Risk mitigation planning and implementation widely used, but not well integrated into the project planning (e.g., cost/work breakdown, integrated schedules)
- Various risk management tools have been used, however , based on NASA trade studies ESMD has selected a state-of-the-art risk tool as the Directorate standard: Active Risk Manager (Strategic Thought, LLP)
- Formal risk management training exists based on Software Engineering Institute risk management process

Evaluation based on OSMA and NASA Center RM POC assessments.

Evaluation of Risk Management State of the Practice

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Risk Management

	Skill	Tool	Process
Prepare for Risk Management			
Determine Risk Sources and Categories			
Define Risk Parameters			
Establish a Risk Management Strategy			
Identify and Analyze Risks			
Identify Risks			
Quantitative			
Qualitative			
Evaluate, Categorize, and Prioritize Risks			
Planning			
Track/Control/Communicate			
Mitigate Risks			
Develop Risk Mitigation Plans			
Implement Risk Mitigation Plans			

Critical Gap	
Significant Gap	
No or Minor Gap	

Gaps

- **Prepare R**
  - Insufficient level of integration of risk management and risk assessment with other capabilities
  - Lack of regular collection of data to assess the level of compliance and practice of risk management and assessment
  - Limited skill, tools and process for in-depth identification of risk sources
  - Limited skill, tools and process for an integrated risk strategy
- **Identify R**
  - Lack of standardization in risk management tools used
  - Inconsistent level of skill and knowledge for Risk Management practioners
  - Insufficient application of quantitative techniques to identify risks, and limited qualitative assessment skills
  - Insufficient skills and tools for a consistent approach to monitoring, tracking, control/feedback and communication (e.g., external) of risks
- **Mitigate Y**
  - Limited skill and tools for mitigation planning
  - Limited skill, tools and process for the implementation of mitigation activities

Requirements/Assumptions for 15.3 Risk Management

- Key Assumption is capability to support key milestones must be in place 5 years prior:
  - 2011 James Webb Telescope
  - 2015 Prepare for Human Lunar Missions
  - 2018 Initial Human Lunar Landings
  - 2025 Extended Lunar Capability
  - 2030 Prepare for Human Mars Mission
- Requirements and assumptions for increased risk management capabilities
  - Increased complexity of systems
  - Increased inter-dependency of complex systems
  - Distributed implementing organizations
  - Environment uncertainty
  - Longer mission durations/complex logistics requirements
  - Tougher science requirements
  - Challenge of implementation and verification of advanced instrument technology (e.g., increased detector sensitivity)
  - Increase future IT capabilities at lower costs

End States

FY 2010 Lunar Support

- **Prepare**
  - Change process and skills to effect integration of risk management
  - Regular collection of self assessment data
  - Institute skills, tools and process for:
    - In-depth identification of risk sources
    - Integrated risk strategies
- **Identify**
  - Standardize risk management tools used
  - Define skills/knowledge criteria for risk practioners; conduct training
    - Including quantitative techniques
  - Institute skills, tools: Monitoring, tracking, control/feedback and communication (e.g., external) of risks
- **Mitigate**
  - Institute skill and tools for mitigation planning
  - Institute skill, tools and process for the implementation of mitigation activities

Top Level Objective of RM 2009 End State

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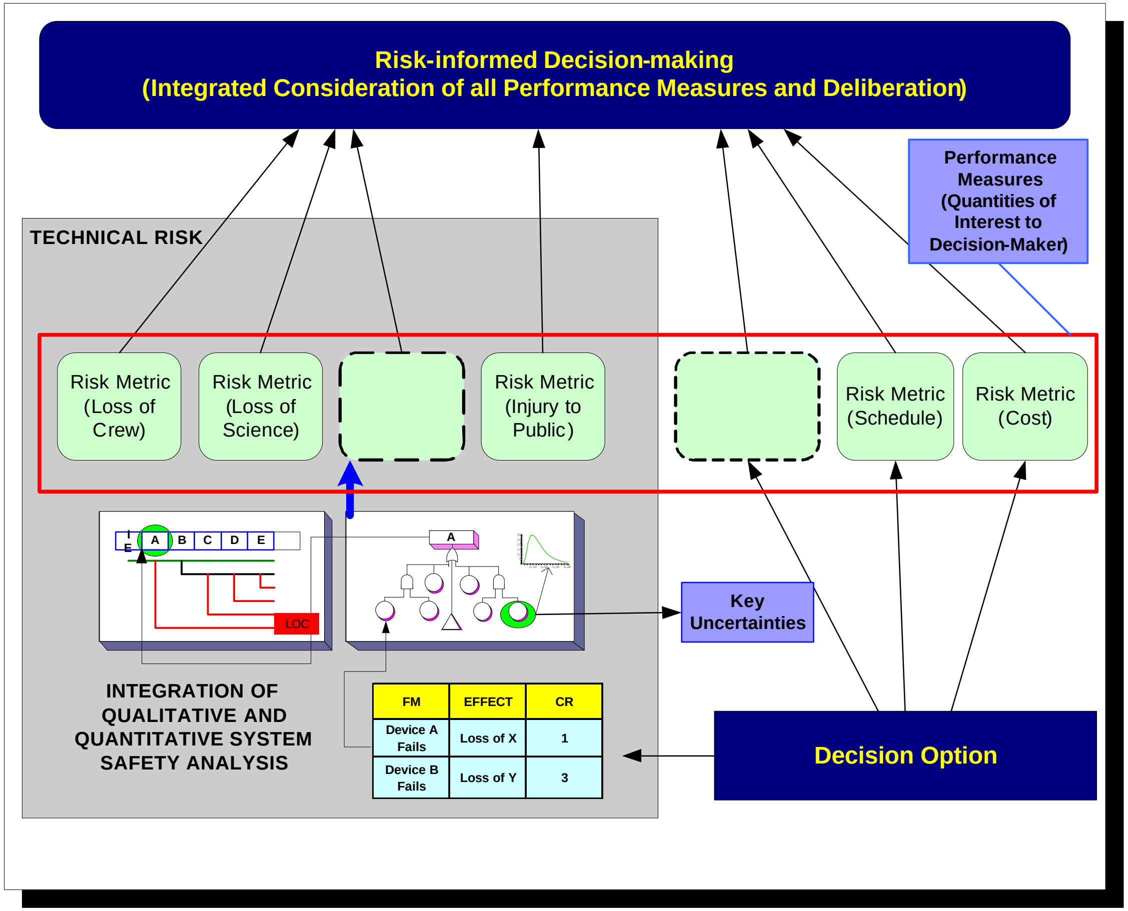
Integration of risk analysis with decision processes



End States (Continued)

FY 2014 Human Lunar Landing Support

- **Prepare**
  - Improved risk source identification; expanded to include routine operational environment challenges
  - Risk sensitivity analysis for interdependent complex systems
- **Identify**
  - Simulation-based risk identification
  - Increased depth and fidelity of quantitative techniques
  - Improved risk communication, including risk uncertainties
- **Mitigate**
  - Integration of mitigation activities into project schedules

End States (Continued)

FY 2020 Extended Lunar Support

- **Prepare**
  - Risk sensitivity analysis techniques for interdependent systems
  - Improved risk source identification; plans for expanded extended lunar operational environment challenges
- **Identify**
  - Predictive risk capability and tools
  - Interactive risk identification; knowledge based providing a connection to risk decisions made in the past
- **Mitigate**
  - Capture of risk mitigation successes/failures to predict mitigation approach probability

End States (Continued)

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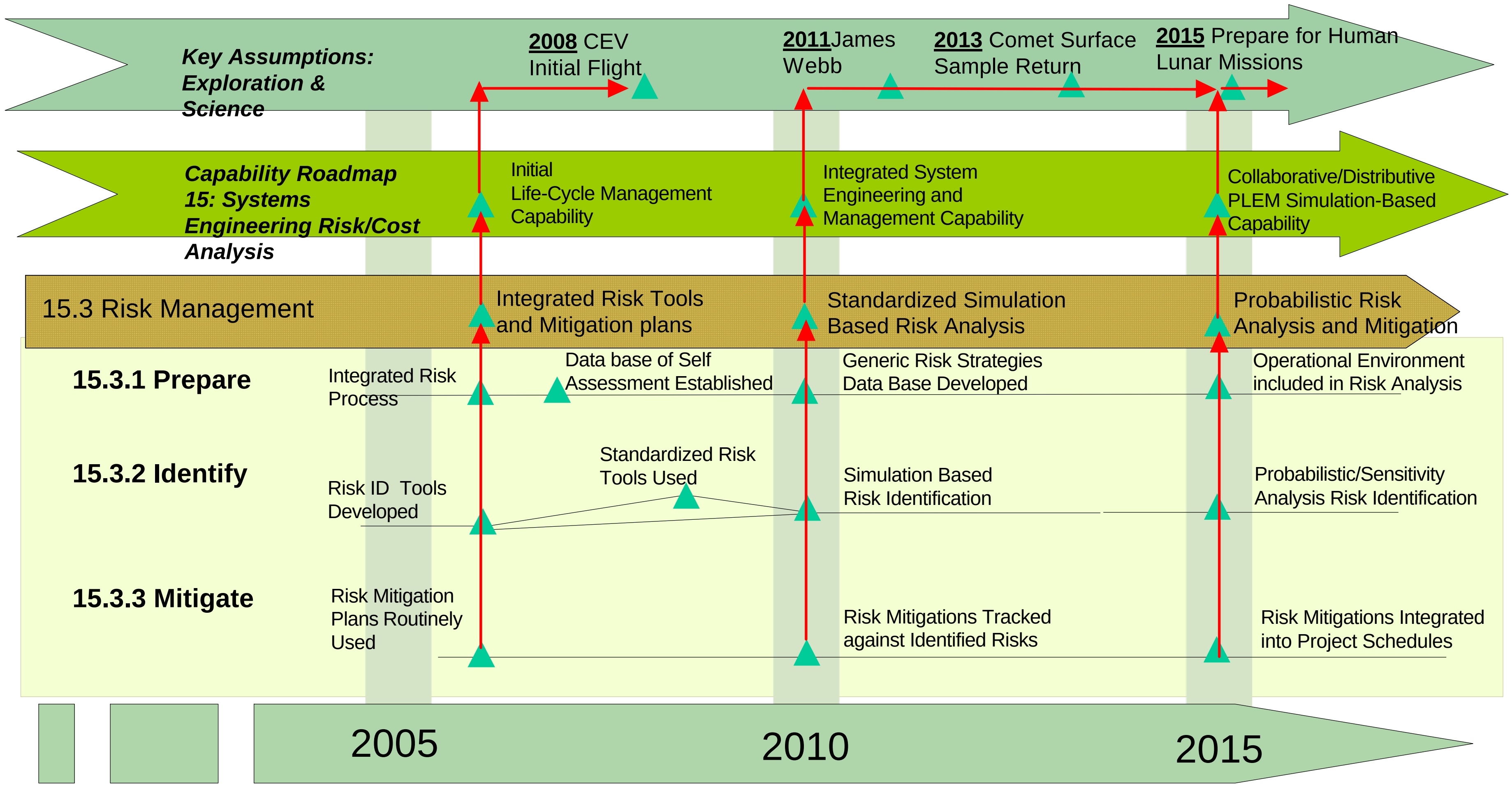
FY 2025 Human Mars Support

- **Prepare**
  - Improved risk sensitivity analysis techniques for interdependent complex systems
  - Improved risk source identification; plans for expanded Mars operational environment challenges

- **Identify**
  - Improved predictive risk capability and tools

Capability 15.3 Risk Management Roadmap



Major Decision

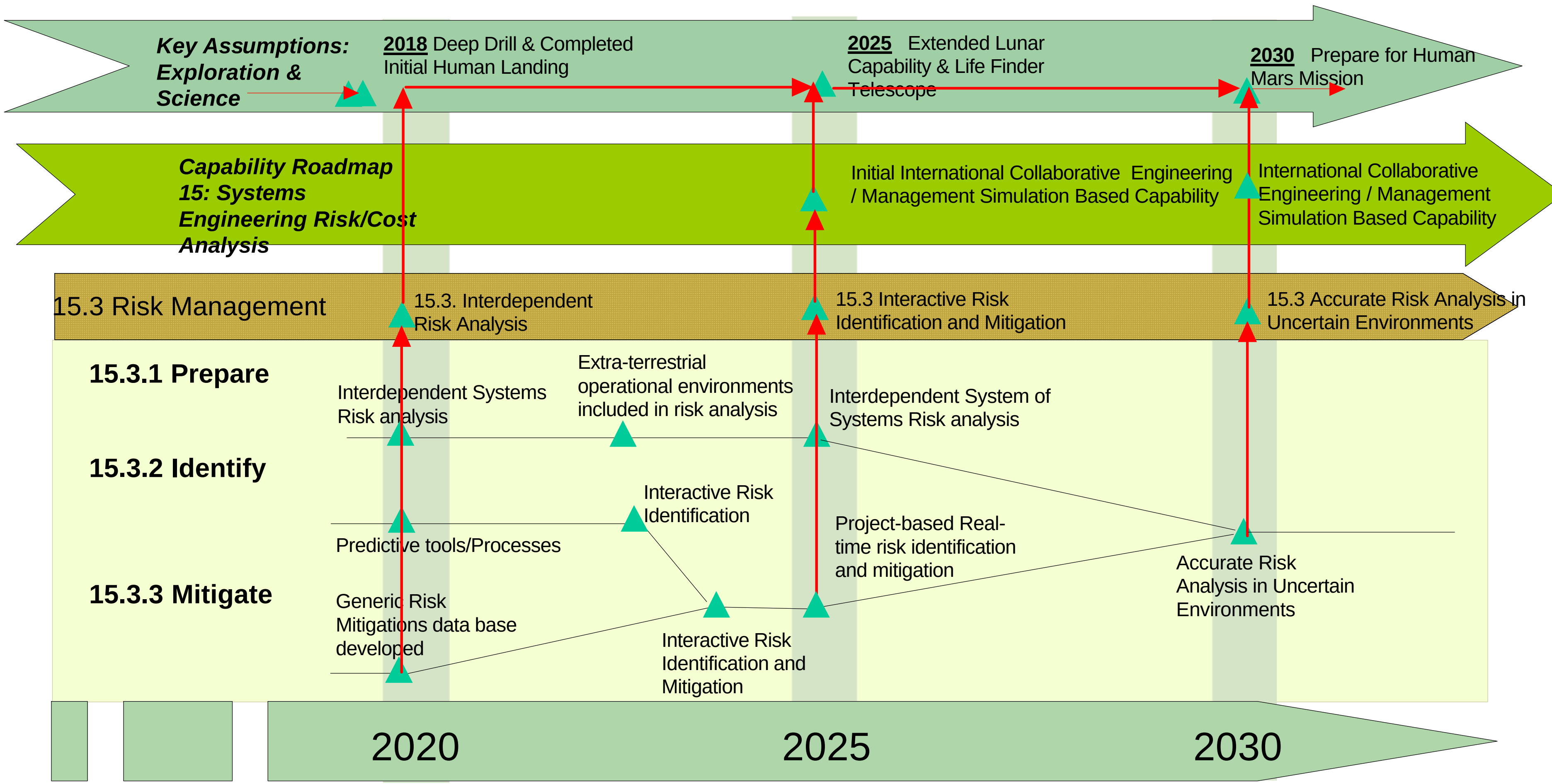
Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product LC Management
SBM – Sim. Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment

Capability 15.3 Risk Management Roadmap



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product LC Management
SBM – Sim. Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment

Maturity Goals

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RISK MANAGEMENT

	2009	2015	2020	2025
Prepare for Risk Management				
Change process and skills to effect integration of RM	6	7	7	7
Regular collection of self assessment data	1/YR	1/YR	1/YR	1/YR
Institute skills, tools and process	80%	100%	100%	100%
Improved risk source identification		6	7	7
Risk sensitivity analysis for interdependent complex systems		6	7	7
Sensitivity analysis techniques for interdependent complex systems			6	7
Improved risk source id; extended lunar operations			6	7
Improved risk source identification; expanded Mars ops				6
Identify and Analyze Risks				
Standardize risk management tools used	6	7	7	7
Define skills/knowledge criteria for risk practioners	6	7	7	7
Institute skills, tools: Monitoring, tracking, control/feedback and communication	6	7	7	7
Simulation-based risk identification		6	7	7
Increased depth and fidelity of quantitative techniques		6	7	7
Improved risk communication, including risk uncertainties		6	7	7
Predictive risk capability and tools			6	7
Interactive risk identification; knowledge based connection to risk decisions made in the past			6	7
Improved predictive risk capability and tools				6
Mitigate Risks				
Institute skills and tools for mitigation planning	6	7	7	7
Institute skill, tools and process for the implementation of mitigation activities		6	7	7
Integration of mitigation activities into project schedules		6	7	7
Capture of risk mitigation successes/failures to predict mitigation approach probability			6	7

Summary

- Risk Management most effective when integrated with program/project and technical management
- First End State targets achieving RM integration with program/project and technical management, and elimination of existing gaps
- End States target delivery of capabilities five years prior to milestone that would benefit most from those capabilities
- Regular evaluation critical to determining capability maturity and success in meeting end state objectives

Capability - 15.4 Safety & Reliability Analysis

Presenter:

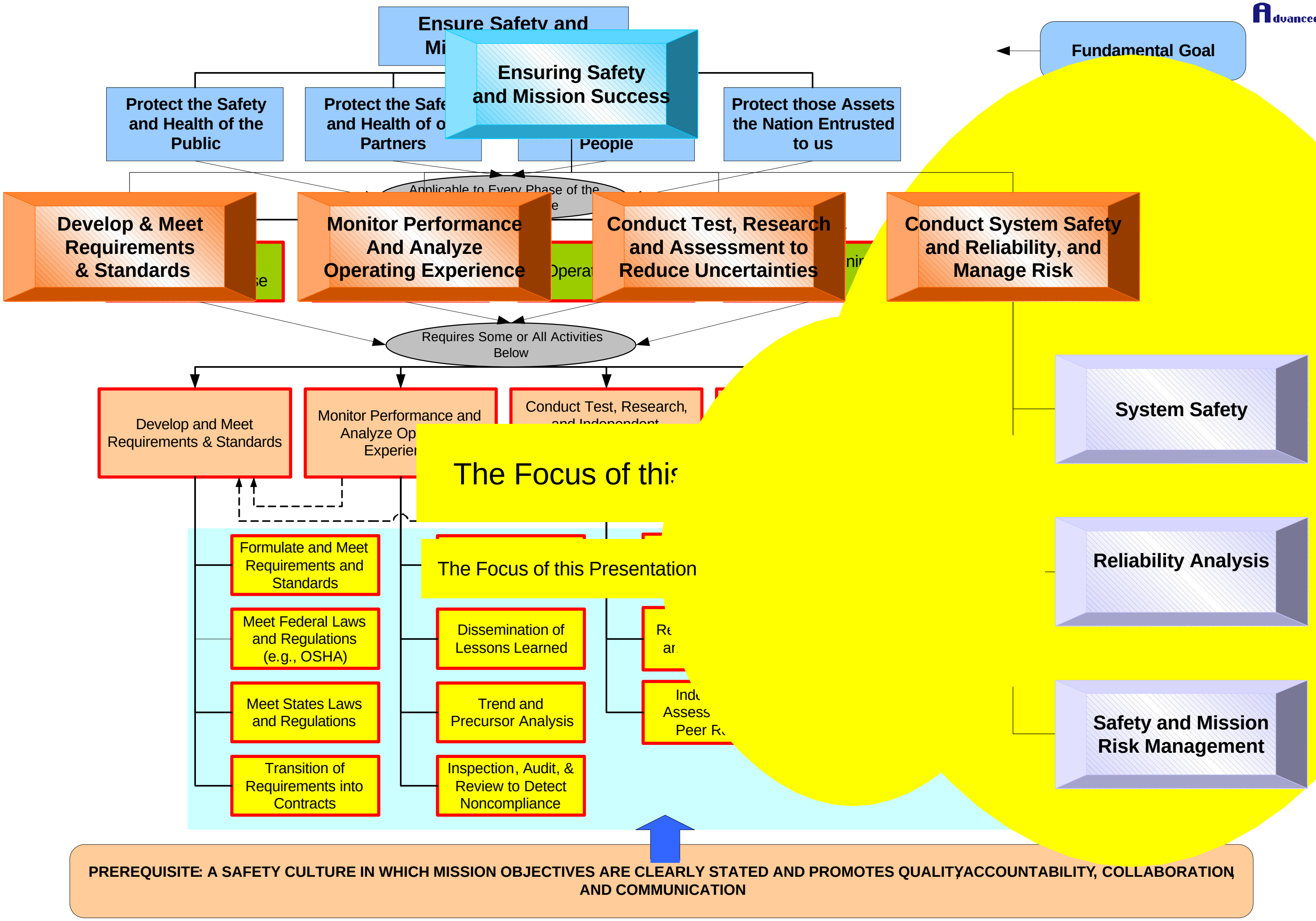
Homayoon Dezfuli, Ph.D, NASA

Team Lead

Objectives of System Safety & Reliability Analysis

- **Evaluation and management of**
  - Safety risk
  - Mission success
- **Includes processes and techniques used to provide organized, disciplined approach to:**
  - Identify and resolve risks as effectively as possible
    - Personnel
    - Equipment
    - Mission success
  - Assess safety and reliability through all phases of the life cycle
  - Risk-informed management of safety & reliability
- **Assessment tools and processes should provide integrated evaluation of the entire system:**
  - Hardware
  - Software
  - Physical environments
  - Operations
  - Human
  - Interactions of systems

Ensuring Safety and Mission Success in an Ideal Decision-making Framework



Benefits of Safety & Reliability Analysis

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- Benefit: Ensure safety and mission success while affordably meeting program objectives

- This benefit will be realized when safety, reliability and risk analyses are standardized and are integrated with decision processes under a single decision-making framework
  - Integrate information on safety, reliability and risk under one umbrella (integration)
    - Elimination of organizational and process barriers
  - Systematize the hazard identification process (modeling standardization)
  - Analyze safety and mission risk (measurement of safety and mission performance)
    - Assessment of aggregate risks
    - Identification of weaknesses and vulnerabilities
    - Identification and assessment of uncertainties
  - Manage safety and mission risk (decision-making)
    - Performance of trade-off studies
    - Development of risk reduction strategies

Current State-of-the-practice for 15.4 Safety & Reliability Analysis

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- **Hazard analysis is widely used**
  - Focuses on specific contributors
  - Limited applicability to complex systems-of-systems
    - generally the result of brainstorming

- **Fault Tree Analysis and Failure Modes and Effects Analysis are widely used**
  - Typically applied when completed design information is available
  - Primarily applied at subsystem level
  - Limited ability to affect early design decisions

- **Risk Matrix is widely used**
  - Applied to top-level risk issues
  - Interaction between risk items is difficult to discern
  - Is unsuitable for combining risks to obtain aggregate risk
  - Uncertainties are not formally accounted for

Example Application of Risk Matrix

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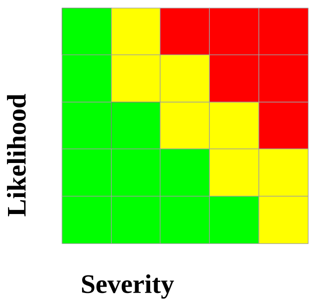
- **A Typical State-of-Practice System Safety Assessment Technique**
  - Analyst postulates a failure or a deviation and assesses its consequences
    - Typically one failure or deviation is analyzed at a time
  - Analyst qualitatively judges how often a failure or deviation can occur
  - Analyst qualitatively judges the severity of the outcome or assumes the worst-case outcome
  - Analyst maps each analyzed failure into one of three risk categories (**Green**, **Yellow**, **Red**)



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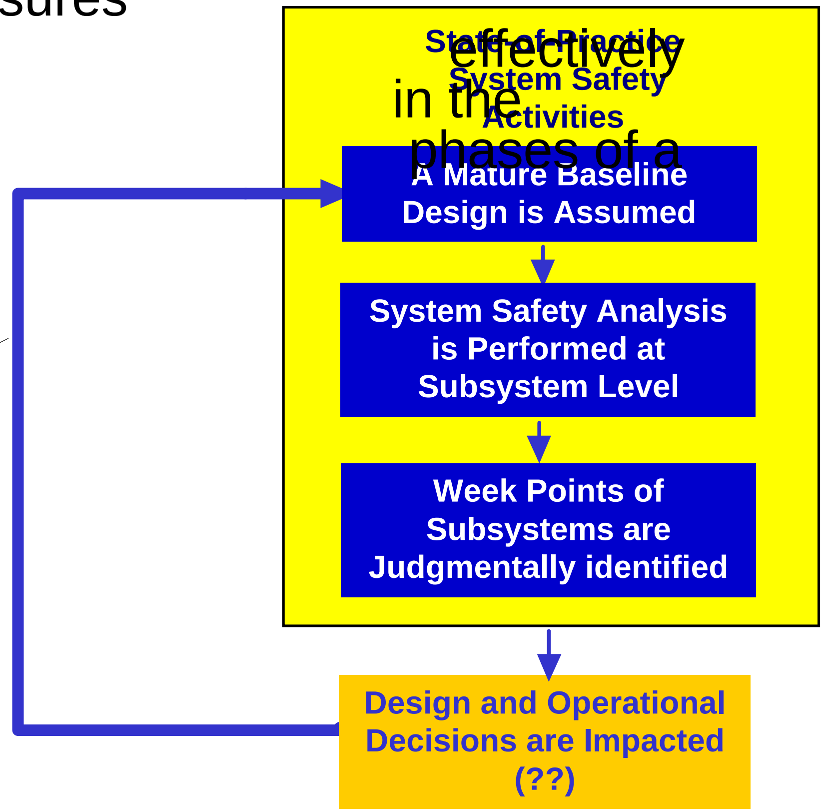
- **The state-of-practice safety analyses does not readily reveal whether safety is improving, declining or staying the same**
  - Not designed to measure safety
  - Without safety performance measures (safety risk metrics) one cannot effectively manage safety risk in the design and operational phases of a system



System safety and risk analyses are organizationally remote from design

They are add-on to traditional engineering analysis

CAIB Report Finding F7.4-4 (Volume I, page 193)

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"System safety engineering and management is separated from mainstream engineering, is not vigorous enough to have an impact on system design, and is hidden in the other safety disciplines at NASA Headquarters."

Current State-of-the-practice for 15.4 Safety & Reliability Analysis (Continued)

- **NASA has begun applying probabilistic risk assessment (PRA) techniques for evaluating safety performance**
  - PRA is shown to be an effective tool
    - To integrate qualitative and quantitative safety models
    - To quantify risk metrics relating to the likelihood and severity of events adverse to safety or mission success including gaining an understanding of uncertainties

- **Probabilistic risk models have not yet been used for design decisions**
  - Models for software-intensive systems, unique space environment, and human decision-making and human-automation interactions have not been fully developed
  - Model developments are hampered by lack of PRA skills and limited and fragmented safety-related reliability databases

Requirements/Assumptions for 15.4 Safety & Reliability Analysis

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- **Robust and effective Safety and Reliability Assessment will be necessary to safely and affordably meet all the goals in the mission framework**
  - ~ 14 launches FY05 -FY10 (not including Shuttle and ISS)
  - Over a hundred launches between FY10 - FY 30
  - Planetary missions using nuclear technology
  - Human mission to Mars by 2030
  - Sample & return missions to Mars in 2014
  - Potential for 3 month stay on the Moon
  - Complex science missions (telescopes and solar exploration)

- **Not limited to human safety and crew survival,**
  - Must include loss of mission, loss of equipment, and adverse environmental impacts

Maturity Level – Capabilities for 15.4 Safety & Reliability Analysis

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	Skills	Tools	Processes
Risk and Safety Management			
Risk Tradeoffs, Risk Acceptance and Risk Communication			
Appreciation and Quantification of Uncertainties			
Mishap Investigation			
Trend and Precursor Analysis			
Dissemination of Lessons Learned			
Systems Safety			
Qualitative Systems Safety Analysis (hardware, **software, phenomenological, human**)			
Quantitative Systems Safety Analysis (hardware, **software, phenomenological, human**)			
System Reliability			
Reliability Prediction Models			
Reliability Database			

Key:

	Minor or No Gap
	Significant Gap
	Critical Gap
Text in red indicates a gap	

Top-level Objective for FY10
15.4 Safety & Reliability Analysis

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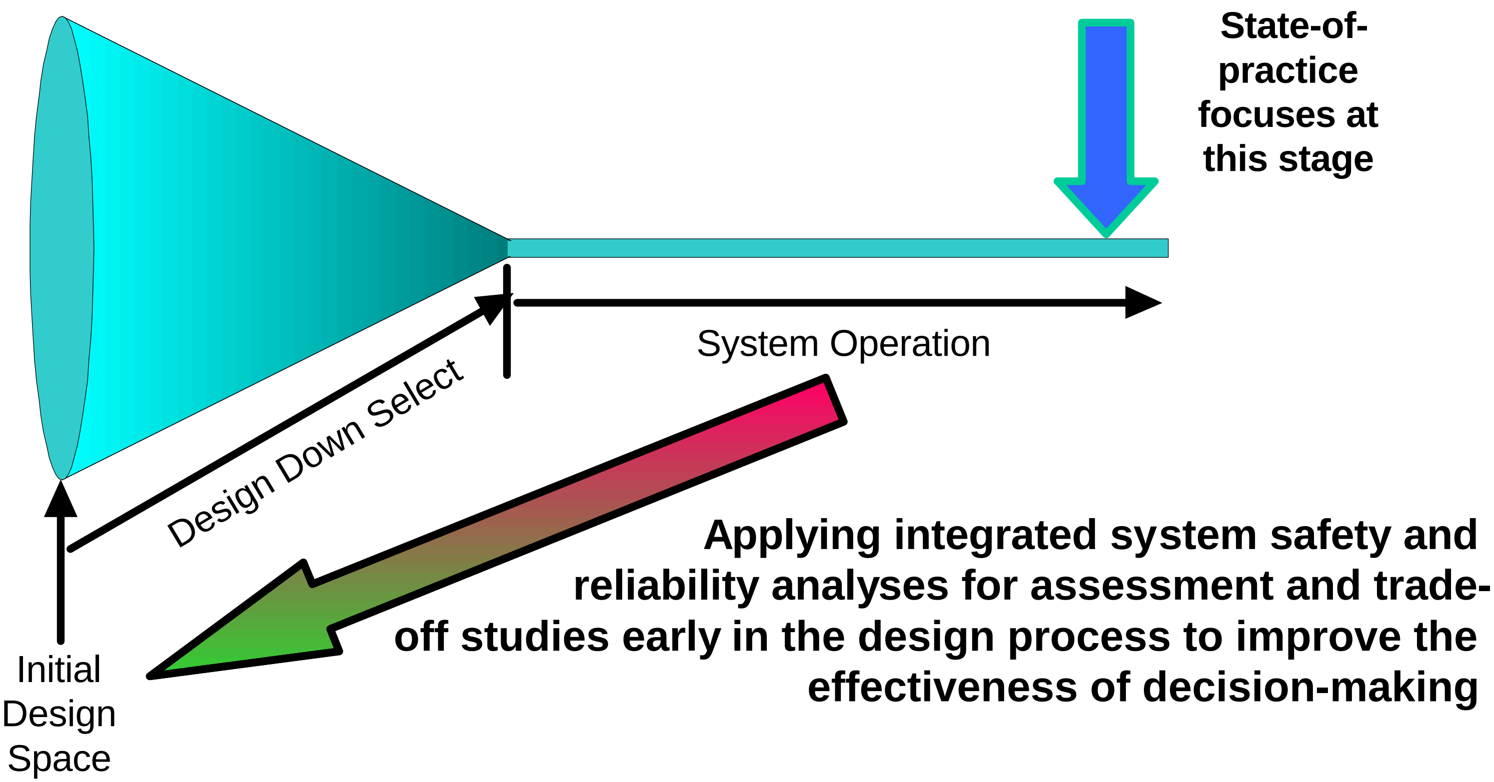
- **Objective: Integration of qualitative and probabilistic methods to support design evaluation**
  - **Integrated qualitative and probabilistic methods are usually not conducted until late in the system life-cycle**



Top-level Objective for FY10 15.4 Safety & Reliability Analysis (Continued)

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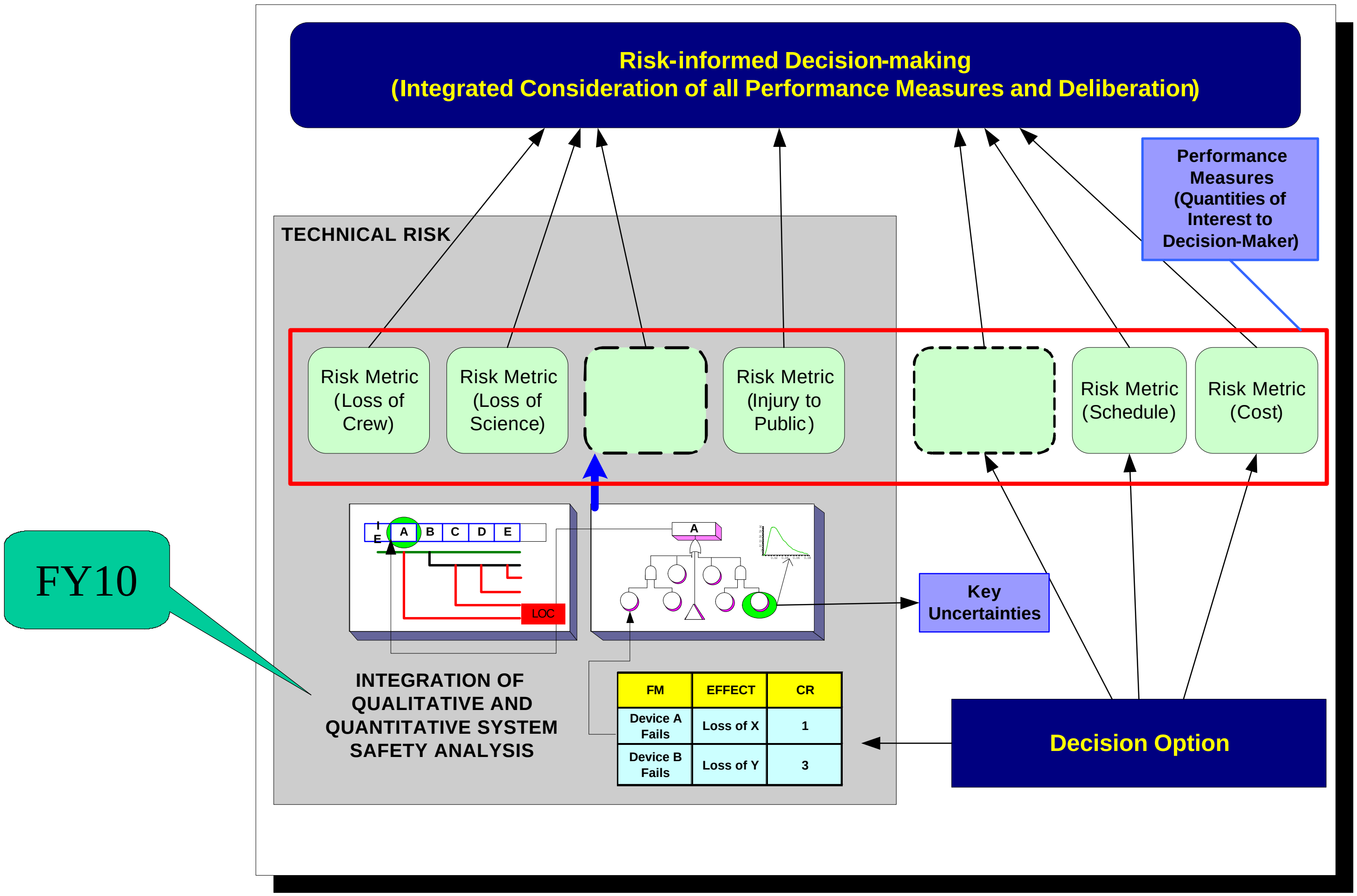
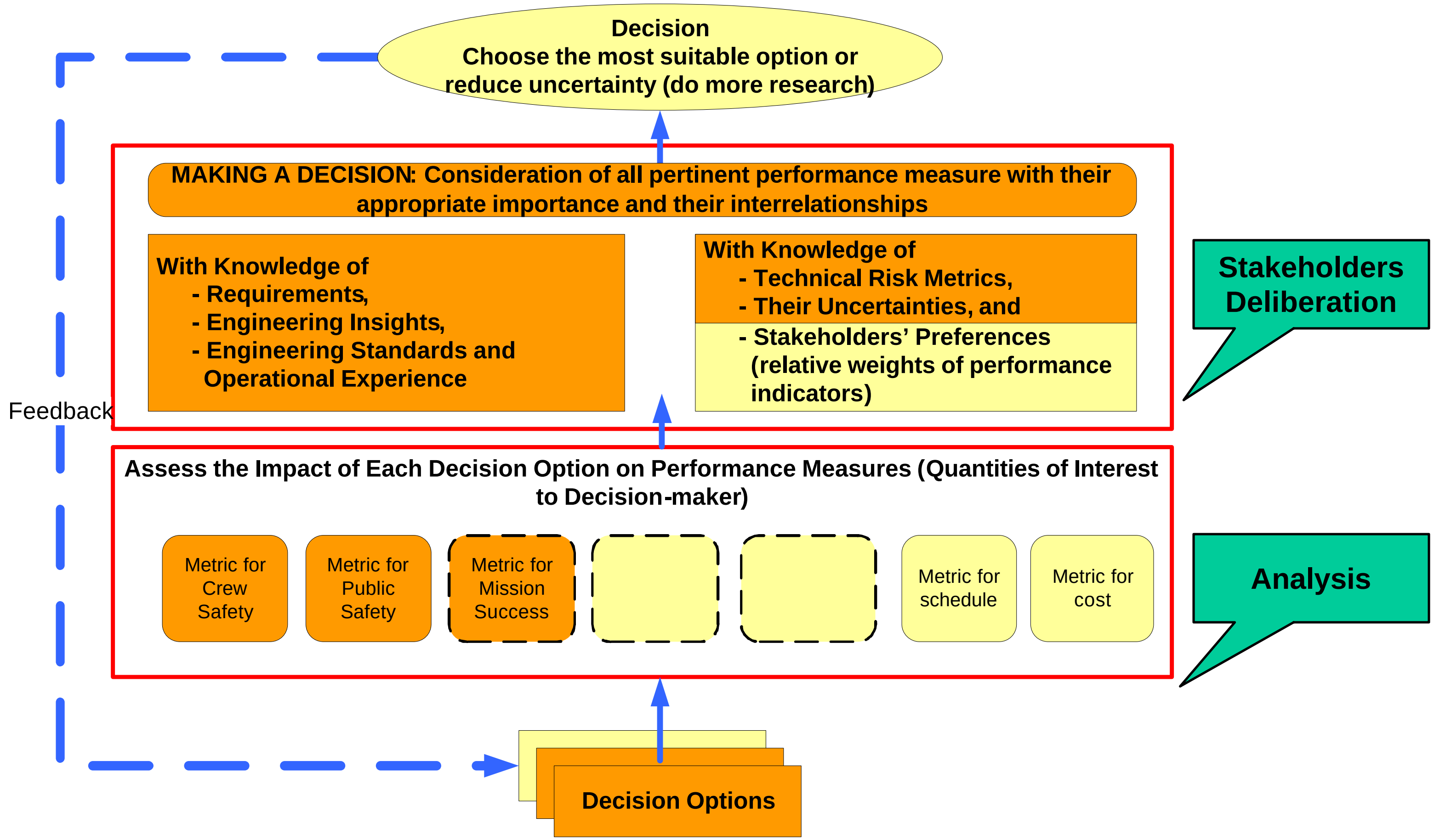
Integration of risk analysis with decision processes



Top-level Objective for FY10 15.4 Safety & Reliability Analysis (Continued)



FY15 Vision for 15.4 Safety & Reliability Analysis

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- **Safety, consistent with mission requirements, is designed into the system in a timely and cost-effective manner**
  - Standardization of safety and reliability analyses and processes and their integration with systems engineering process
  - Ability to trade safety & reliability against performance, cost, design options, diverse management paths
  - Extend analysis philosophy to development stages of system design
  - Developing risk acceptance process and criteria
  - Ability to assess and quantify uncertainties
  - Ability to perform trend and precursor analysis
  - Systems knowledgeable safety experts

- **Physics-based Probabilistic Risk Assessment Models that fully integrate all elements of risk; including technical, organizational, and cost**
  - Centralize existing safety, reliability, system design/operating limitations, and risk focused database
  - Assessing expected performance of a design / operational strategy, based on probabilistic simulation of time histories and explicit evaluation of performance (risk) metrics for those time histories
  - User-friendly, intuitive safety & reliability tool interfaces
  - Risk models linked directly to database with automated evaluation updates

Top-level Objective for FY15
15.4 Safety & Reliability Analysis

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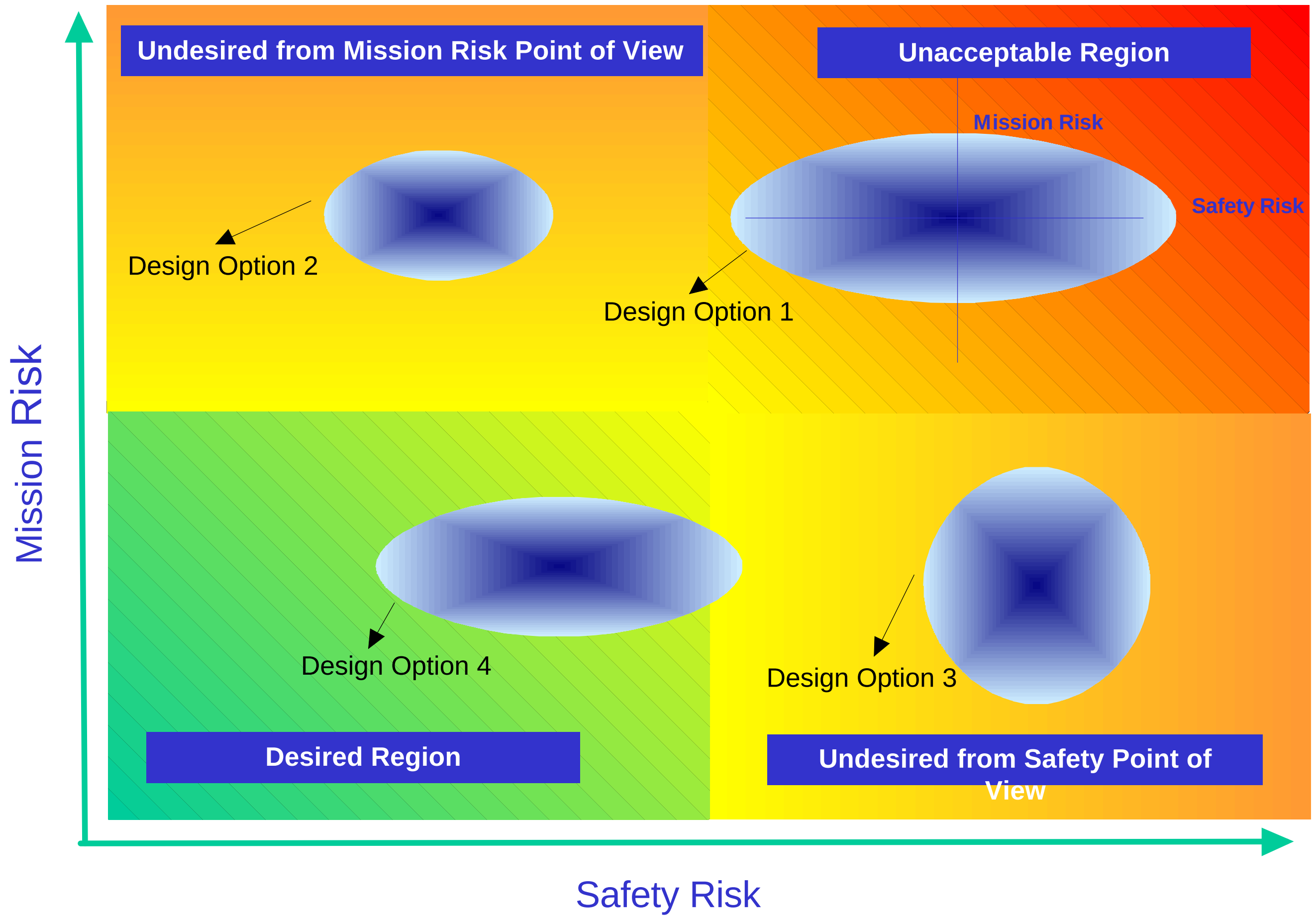


Defining acceptable risk regions specific to the program

Risk assessment of decision options

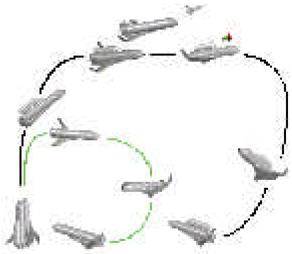
Assessment of uncertainties

consideration of risk results including their uncertainties in decision-making

Example Integrated Future Capability

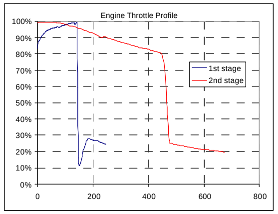
Architecture Definition

Mission Profile

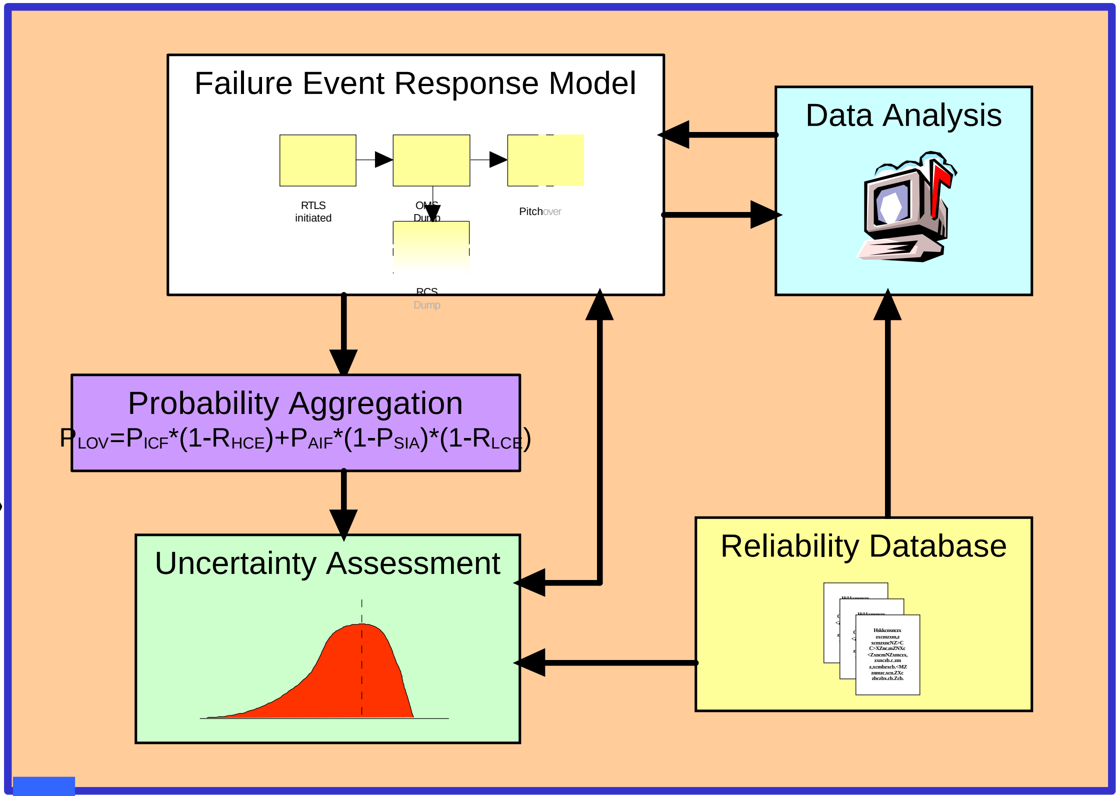


Inputs

Operational Parameters



Failure Modeling



Outputs

Loss-of-Crew (LOC) Probability Distribution

Loss-of-Vehicle (LOV) Probability Distribution

Loss-of-Mission (LOM) Probability Distribution

Other Risk Metrics

FY30 Vision for 15.4 Safety & Reliability Analysis

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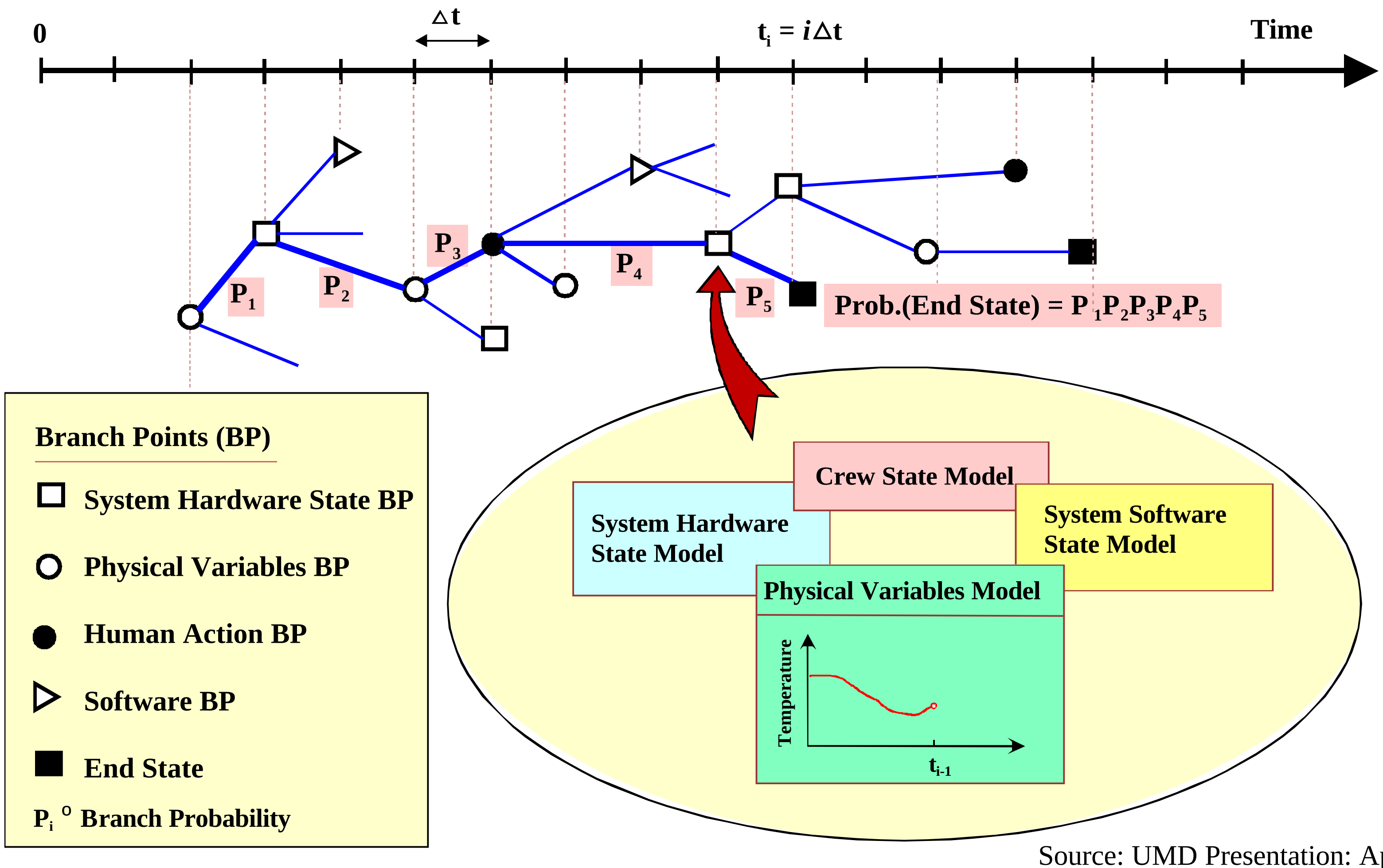
- **System safety and reliability activities incorporated in a risk-informed decision-making framework, capable of**
  - Responding to mishaps in real time
  - Allocating resources (presents solutions, evaluates mitigation options)
  - Effective communication of safety issues
  - Monitoring performance using well defined risk metrics

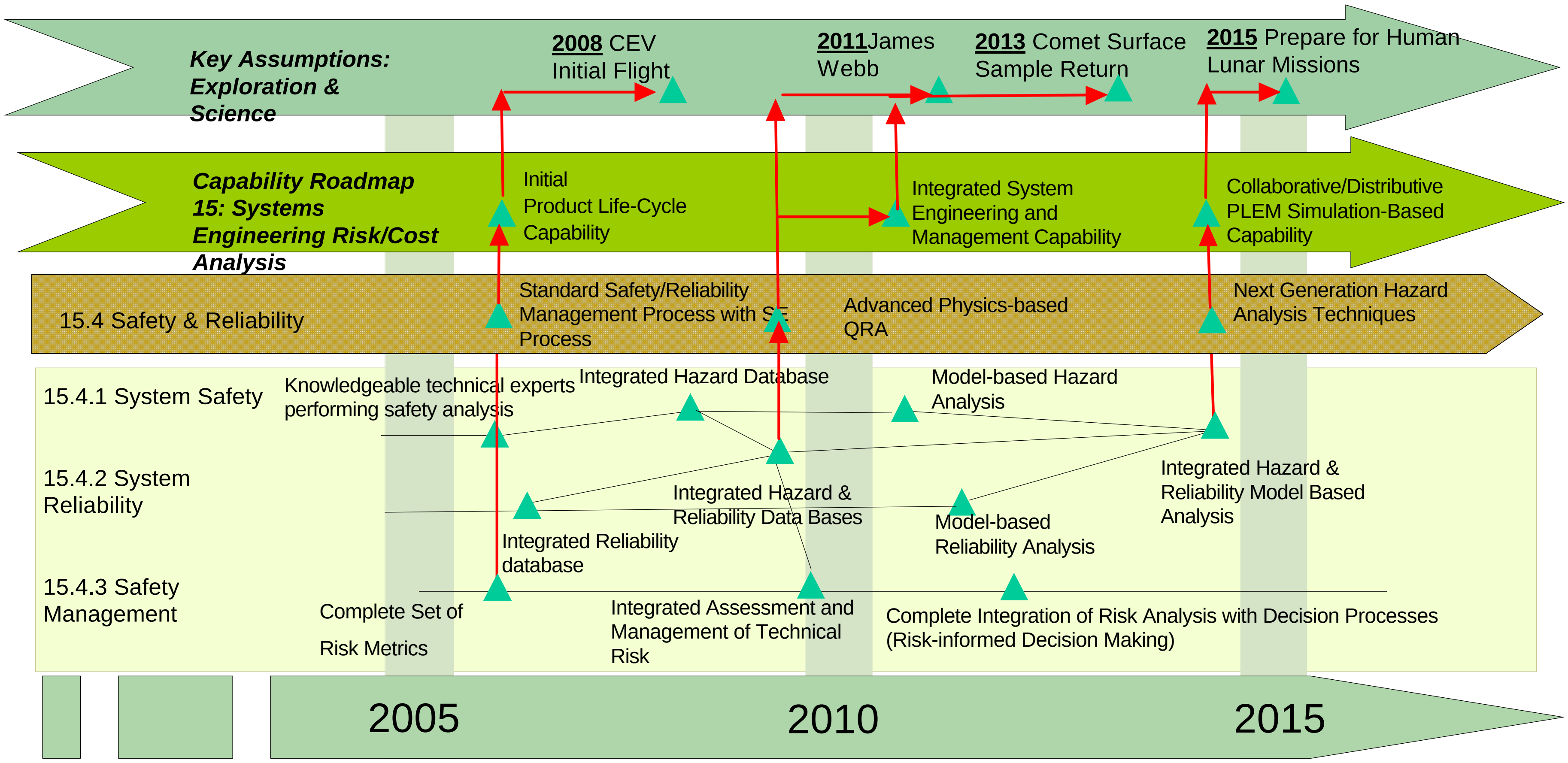
- **Virtual life-cycle simulation model of safety & reliability**
  - Next-generation hazard analysis techniques that evaluate
    - New hardware technology
    - Software
    - human performance
    - Organizational factors
  - Safety and reliability models that interface with
    - Quality control processes
    - Testing processes
    - Assembly and manufacturing
    - Maintenance and operational processes

Example of a Simulation-based Risk Model



Source: UMD Presentation: April 04

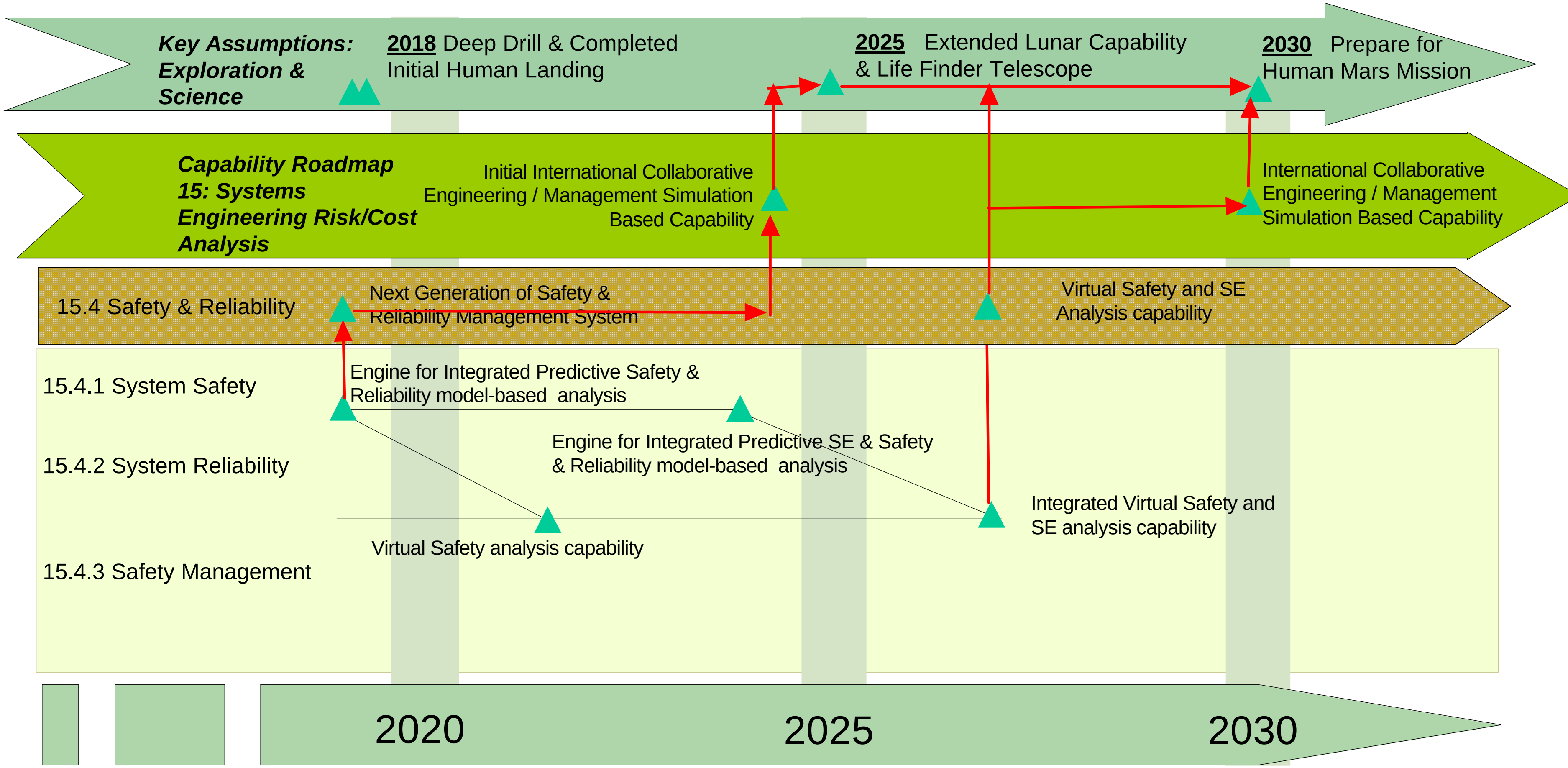
15.4 Safety & Reliability Analysis



Major Decision
Major Event / Accomplishment / Milestone
Ready to Use

Legend
PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

15.4 Safety & Reliability Analysis



Major Decision

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Ready to Use

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PLM – Product Life Cycle Management
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CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Concluding Summary

Presenter:

Stephen Cavanaugh

Capabilities Current State

Advanced Planning & Integration Office

Systems Engineering

SE-CMMI			Team Assessment
	ENGINEERING		
		REQUIREMENTS DEVELOPMENT	
		REQUIREMENTS MANAGEMENT	
		TECHNICAL SOLUTION	
		PRODUCT INTEGRATION	
		VERIFICATION	
		VALIDATION	
	PROJECT MANAGEMENT		
		PROJECT PLANNING	
		PROJECT MONITORING AND CONTROL	
		SUPPLIER AGREEMENT MANAGEMENT	
		INTEGRATED PROJECT MANAGEMENT FOR IPPD	
		RISK MANAGEMENT	
		INTEGRATED TEAMING	
		INTEGRATED SUPPLIER MANAGEMENT	
		QUANTITATIVE PROJECT MANAGEMENT	
	SUPPORT		
		CONFIGURATION MANAGEMENT	
		PROCESS AND PRODUCT QUALITY ASSURANCE	
		MEASUREMENT AND ANALYSIS	
		DECISION ANALYSIS AND RESOLUTION	
		ORGANIZATIONAL ENVIRONMENT FOR INTEGRATION	
		CAUSAL ANALYSIS AND RESOLUTION	
	PROCESS MANAGEMENT		
		ORGANIZATIONAL PROCESS FOCUS	
		ORGANIZATIONAL PROCESS DEFINITION	
		ORGANIZATIONAL TRAINING	
		ORGANIZATIONAL PROCESS PERFORMANCE	
		ORGANIZATIONAL INNOVATION AND DEPLOYMENT	

Life Cycle Costing

Robototic Spacecraft

Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation			
Development			
Production			
Operations			

Human Spaceflight

Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation			
Development			
Production			
Operations			

Risk Management

	Skill	Tool	Process
Prepare for Risk Management			
Determine Risk Sources and Categories			
Define Risk Parameters			
Establish a Risk Management Strategy			
Identify and Analyze Risks			
Identify Risks			
Quantitative			
Qualitative			
Evaluate, Categorize, and Prioritize Risks			
Planning			
Track/Control/Communicate			
Mitigate Risks			
Develop Risk Mitigation Plans			
Implement Risk Mitigation Plans			

Safety & Reliability Analysis

	Skills	Tools	Processes
Risk and Safety Management			
Risk Tradeoffs, Risk Acceptance and Risk Communication			
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Mishap Investigation			
Trend and Precursor Analysis			
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System Reliability			
Reliability Prediction Models			
Reliability Database			

Critical Gap	
Significant Gap	
No or Minor Gap	

Key:

	Minor or No Gap
	Significant Gap
	Critical Gap
Text in red indicates a gap	

Systems Engineering Cost/Risk Analysis Roadmap Metrics

- Development Metrics (process, skills, tools)
  - Annual SE NASA modified CMMI audit of maturity (levels 1-5) and capability readiness (levels 1-5)
  - Number of NASA certified engineers in Systems Engineering, Life-Cycle Costing, Risk Management, and Safety
  - Percentage of programs using integrated Systems Engineering, Project Management, Life-Cycle Costing, Risk Management, and Safety tools
- Performance Metrics (implementation)
  - Number of cancelled programs and termination reviews per year
  - Average percent cost of overrun per year
  - Accuracy of cost and schedule predictions
  - Percent of program cost dedicated to Systems Engineering
  - Number of mission failures per total number of missions
  - Number of hits (requests) from Knowledge Management databases in Cost, Reliability, Safety, Risk, and Systems Engineering

Systems Engineering Cost/Risk Analysis Roadmap Program Review

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- Do the Capability Roadmaps provide a clear path way to technology and capability development?
  - Yes. All Roadmap sections address skills, tools (including Database creation from which Models are developed to address current gaps), and new process.
- Are technology maturity levels accurately conveyed and used?
  - Yes. CRL were assessed by the community, and programs created to address areas with low level CRLs.
- Are proper metrics for measuring advancement of technical maturity included?
  - Yes. The development and performance metrics assigned are appropriate to measure progress towards increasing the validity of the discipline, and reflect current Government criticism.
- Do the Capability Roadmaps have connection point to each other when appropriate?
  - Yes. The capability is a discipline which connects to all other roadmaps.

NASA Systems Engineering Cost/Risk Analysis Roadmap Team Summary

Advanced Planning & Integration Office

- An active Senior Sponsor is ***absolutely essential*** due to the complexity of future NASA Exploration missions
- Develop an Integrated organization of Systems Engineering, Cost, Risk, & Safety
  - Application needs to be strategic and tactical implementation
  - Capability to integrate across Agency are currently uneven
- Develop a Systems Engineering, Cost, Risk and Safety Professional Certification program to develop a qualified skill base
  - Require SE certification level for all SE positions
  - Require as a performance objective in personnel reviews
  - Reward progress
- Establish an independent review process for each program that provides a gate keeping processes to ensure project success
- Create a centralized archival database with best practices, skill base, processes, and lessons learned

The state of systems engineering as practiced at NASA needs to be improved to successfully achieve the Exploration Vision.

DoD Partnering Possibilities

- Both part of the U.S. government with all the general rules, regulations and procedures that entails
- Share a common industrial base
- Anticipate a large turn over of the workforce in the near future
- Funding constraints, including uncertainties from budget cuts
- Moving towards capabilities-based acquisition and evolutionary development
- Increasing complexity with more system-of-systems and families-of-systems
- Share some technology overlap
- Need a strong role of Systems Engineering Systems Engineering, Cost, Risk and Safety within our programs to be successful

Opportunity exists to collaborate with DoD & NROs Systems Engineering Professional Development Program and the established Systems Engineering Education programs at DAU & AFIT.

Next Steps/Forward Work

Advanced Planning & Integration Office

- Make changes to roadmaps based on NRC feedback
- Review and Assess all applicable Strategic Roadmaps and their requirements for Systems Engineering capabilities
  - Suggest possible opportunities for Strategic Roadmaps
- Make changes to roadmaps to ensure consistency with Strategic Roadmaps requirements
  - Additional metrics to determine if achievements will be reached
- Continue to work with other Capability roadmaps to ensure consistency and completeness
- Develop rough order of magnitude cost estimates for the Systems Engineering, Cost, Risk and Safety Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

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Capability Readiness Level Rating

7 – Commercial processes/tools widely used by industry and NASA

6 – Commercial processes/tools sparsely used by NASA

5 – Specialized NASA developed processes/tools used in current programs

3 – Processes/tools under development for existing projects/programs

1 – Ideas of processes/tools that could enhance NASAs Systems Engineering