Structuring T&E for Validation of Complex Systems Capabilities and Exploration of Emergent Behaviors

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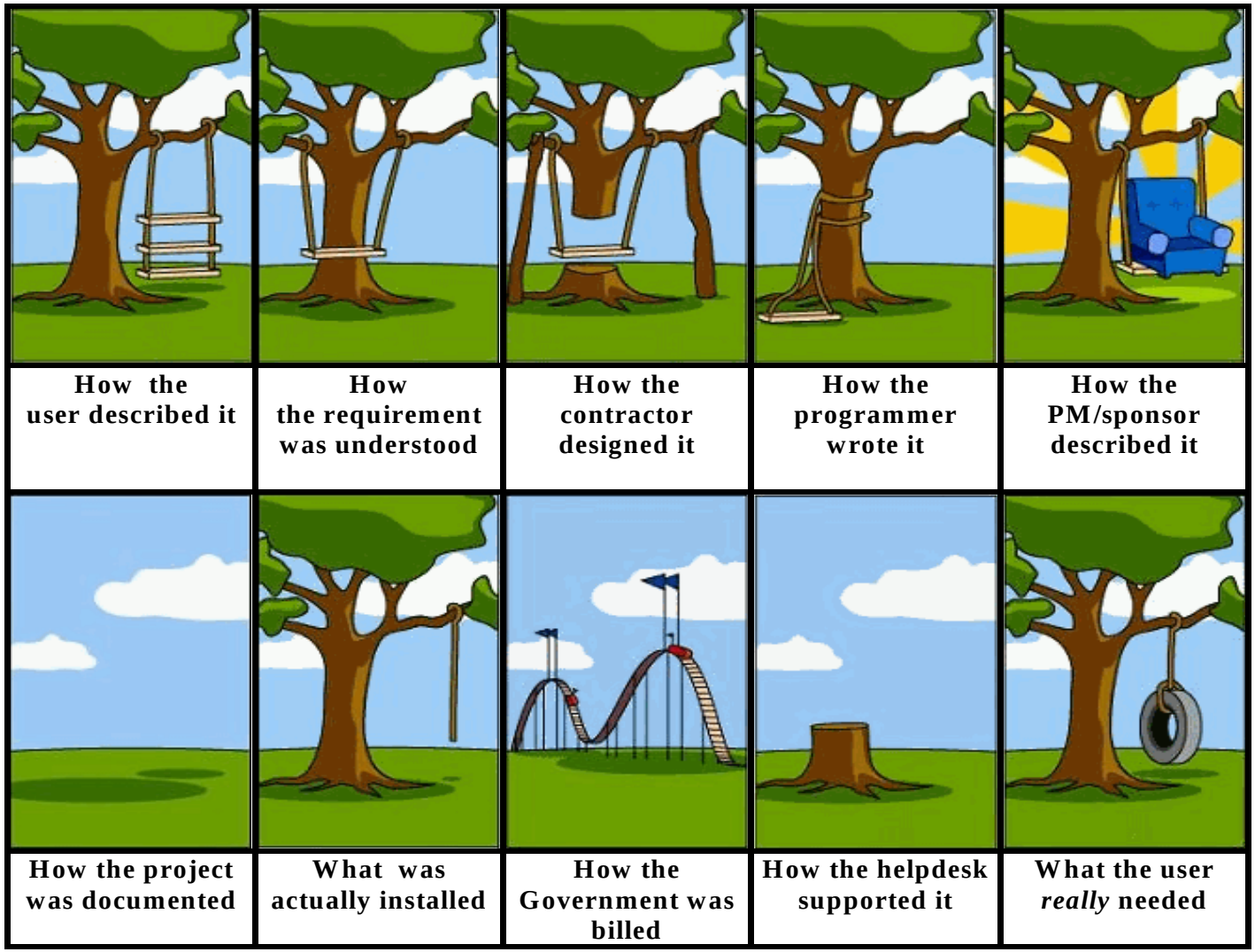
Agenda

- SYSTEMS THEORY RELEVANT TO T&E
  - Complex Systems
  - Holism
  - Emergence
- STRUCTURING T&E FOR VALIDATION OF COMPLEX SYSTEMS
  - Complex System V&V
  - Complex System T&E
  - Considerations and Recommendations
    - Mission and Functional Analysis Based Test Planning
    - Risk Prioritized Integrated Testing across the Development Life-Cycle
    - Design of Experiments Based Test Planning and Analysis
- CONCLUSION

Systems Engineering
The way it really is?



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SYSTEMS THEORY RELEVANT TO T&E

- Complex Systems
- Holism
- Emergence

Complex Systems

- **Holistic**, hierarchal, transient, **emergent,** non-deterministic, large number of elements and states, etc...

- **Detail complexity**—hierarchical relationships dominate; complex in size and scope but straight forward causal relationships; somewhat predictable; risks in contributing parts (Calvano & John, 2004)

- **Dynamic complexity**—lateral interfaces dominate; complex integration and behaviors; unpredictable; system risks dominate; causal relationships difficult if not impossible to determine (Calvano & John, 2004)

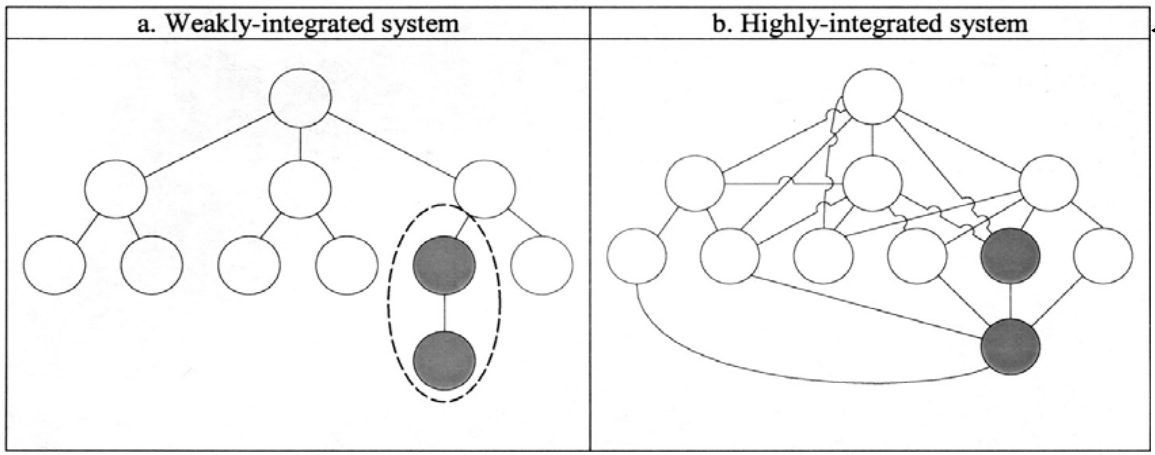
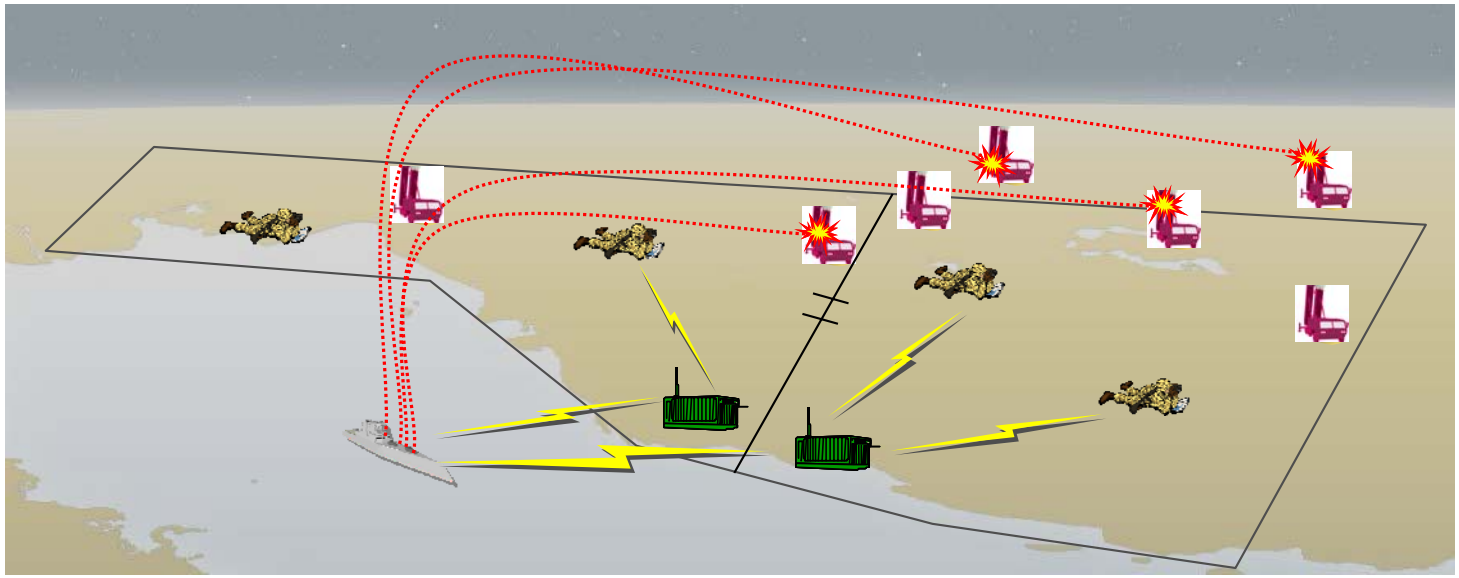


Figure from Calvano, C. & John, P. (2004). "Systems Engineering in an Age of Complexity," *Systems Engineering, 7*(1), p. 27.

Complex Systems Example:
Naval Surface Fire Support



- Very Complex System; also possibly a System of Systems
- Dynamic Complexity – many parts, high degree of coupling and interaction across a large number of complex interfaces; integration challenge!
- Diverse, separated, component systems; transient states & deterministic behavior
- Variability and unpredictability of human behaviors and interaction w/ system
- Emergent behaviors from coupling of sensors, weapons, & employment methods

Holism

- “A system has holistic properties possessed by none of its parts. Each of the system parts has properties not possessed by the system as a whole.” Clemson (1984, p. 201)
- Holism emphasizes whole over parts; organizational level analysis ensuring elements function together to serve the purpose of the system. Jackson (2006, p. 650)
- Reductionism serves to help in building up a system design, but a holistic view is needed in order to evaluate complex systems.

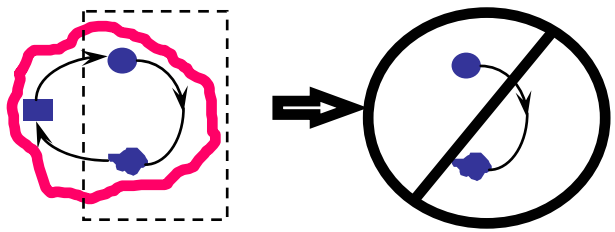


Figure from Old Dominion University ENMA 640 and ENMA 715 Course Presentations

Emergence

- A systems principle that whole entities exhibit properties that are meaningful only when attributed to the whole, not its parts – e.g. the pungent smell of ammonia, which comes from the properties of the molecule, not those of the constituent nitrogen and hydrogen atoms. (Hitchens, 2003)

- Generally accepted aspects of emergence (see backup slides for references from literature):
  - Unpredictable / unexpected
  - Derives from integration, interfaces, and interaction of the systems' elements
  - Not present in the systems' elements nor can it be predicted by evaluating each of those – although can influence them

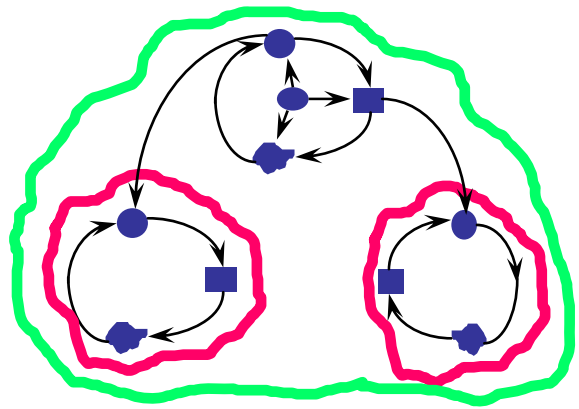


Figure from Old Dominion University ENMA 640 and ENMA 715 Course Presentations

Emergence?

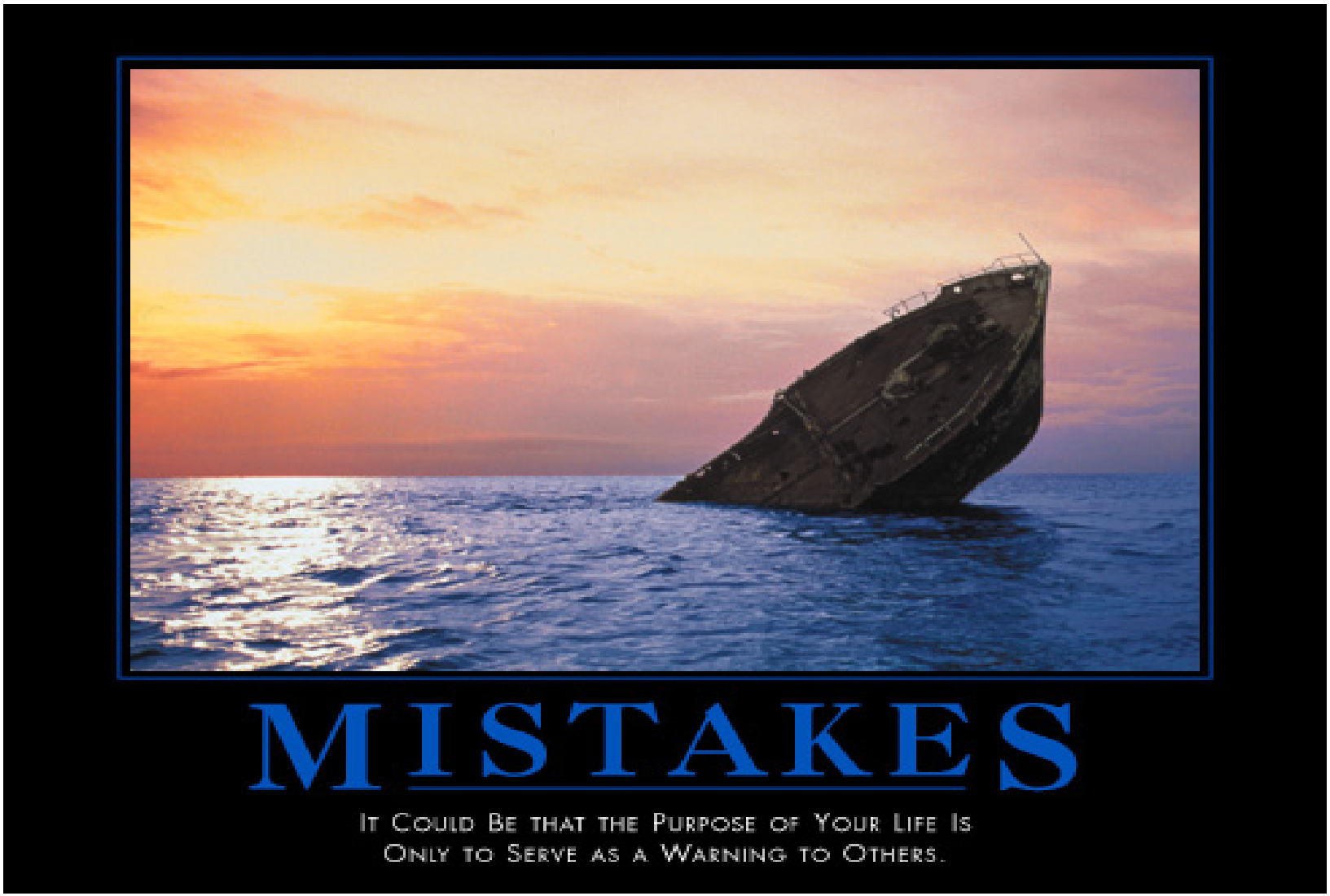


Figure from www.despair.com

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STRUCTURING T&E FOR VALIDATION OF COMPLEX SYSTEMS

- Complex System V&V
- Complex System T&E
- Considerations and Recommendations

Verification & Validation

- **Verification:** Confirmation by examination and provisions of objective evidence, that specified requirements have been fulfilled. (IEEE Std 1012, 1998, p.71)

  Did you build what you said you were going to build?

- **Validation:** Confirmation by examination and provisions of objective evidence that the particular requirements for a specific intended use are fulfilled. (IEEE Std 1012, 1998, p.71)

  Did you build what the user needed?

- V&V is a broad set of activities for software or whole systems applied across the life-cycle, supporting a variety of activities from assessing technical alternatives in conceptual design to ensuring the as-built system meets its specifications and the user's need.

What encompasses a user's needs?

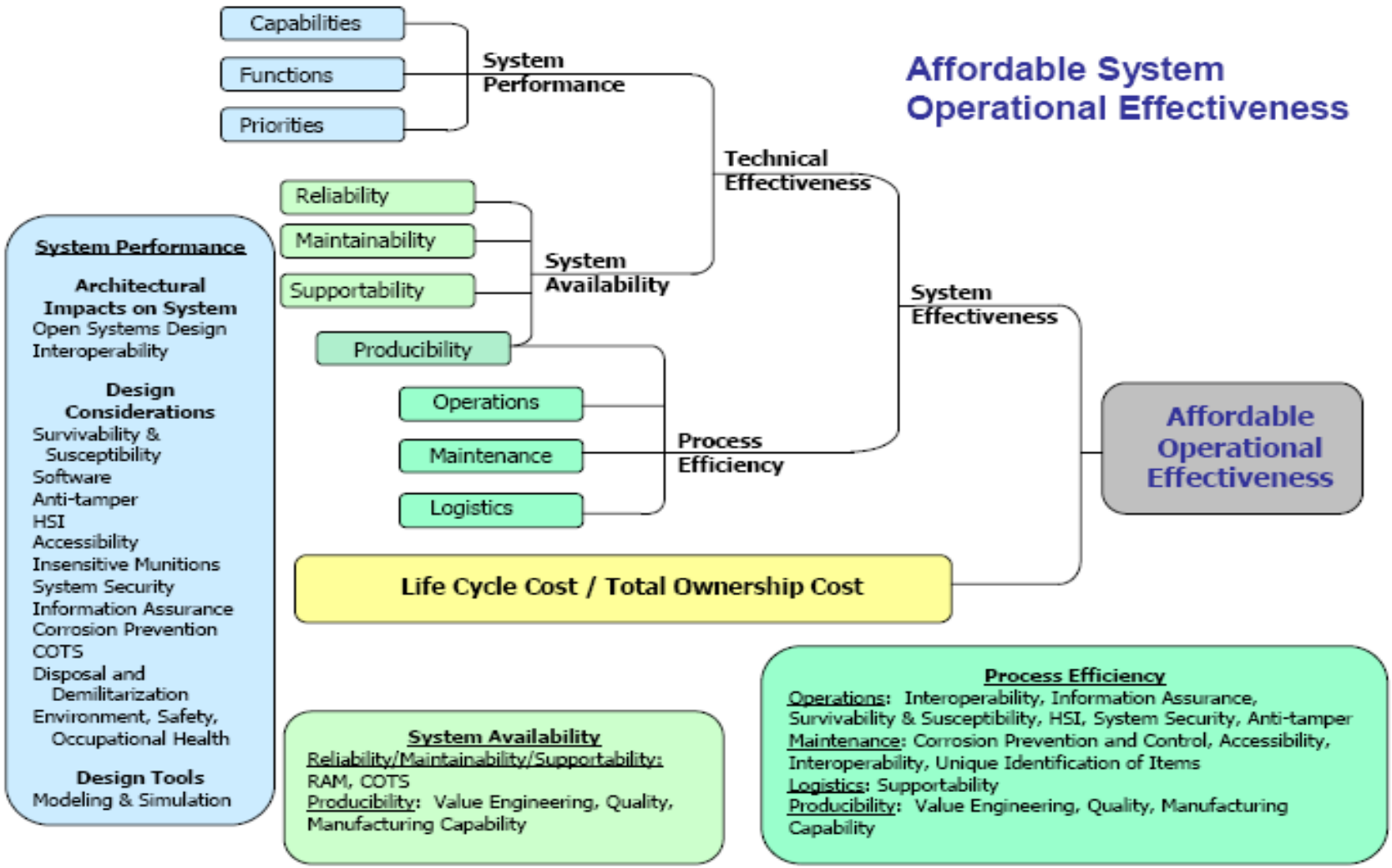


Figure from *DoD Acquisition Guidebook* (2006). Washington, DC: OSD AT&L. p. 141.

Test & Evaluation

- Test = procedure to measure performance under various conditions. (Parker, 1994)

- Testing = linchpin, intelligence/feedback loop for systems engineering. (Laskey,1999, p. 6)

- T&E at its best = goal to provide necessary info to ensure quality.

  At its worst = political game where programs fight for survival and money. (Laskey,1999, p. 6)

- T&E ~ experiment & theory; predict outcome, validate points of doubt (Goode & Machol (1957, p. 509)
  - –Unfortunately complex systems are often non-deterministic if not completely unpredictable

Focus of T&E

- "How well did the system actually perform, and did it accomplish its mission objective?" –
  - Mission accomplishment not just specs
  - System effectiveness + Support system capability (suitability)

- "Does the system meet all of the requirements as covered through the specified technical performance measures?"
  - Technical verification; developmental testing

- "Does the system meet all [user] requirements?"
  - Verification and validation?
  - Could a system meet the user's requirements as stated and yet be not operationally effective/not suitable?

Blanchard (2008, p. 113)

Complex Systems Engineering + V&V / T&E

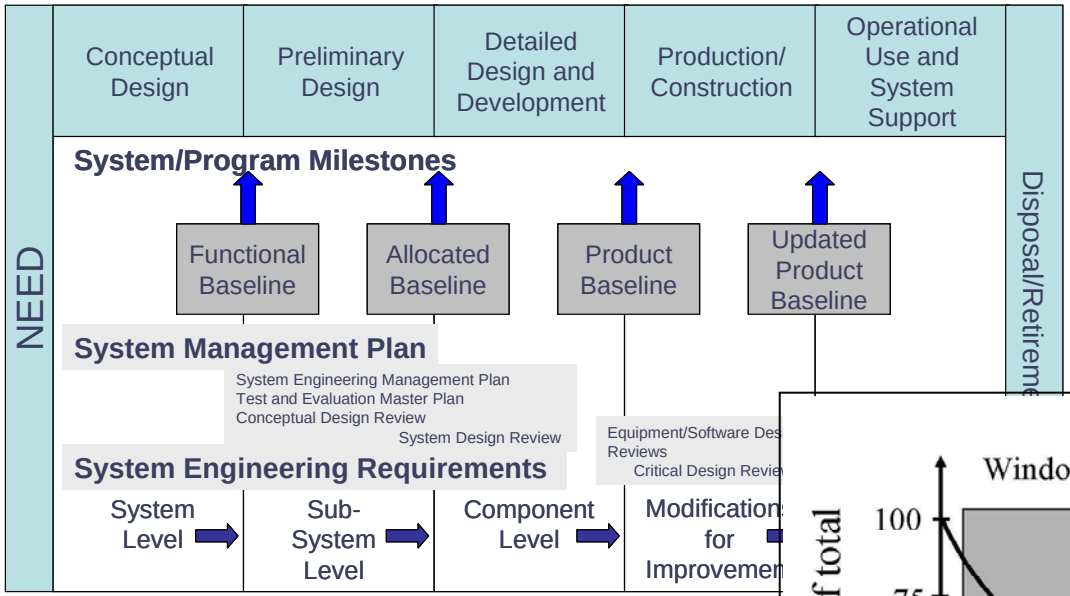
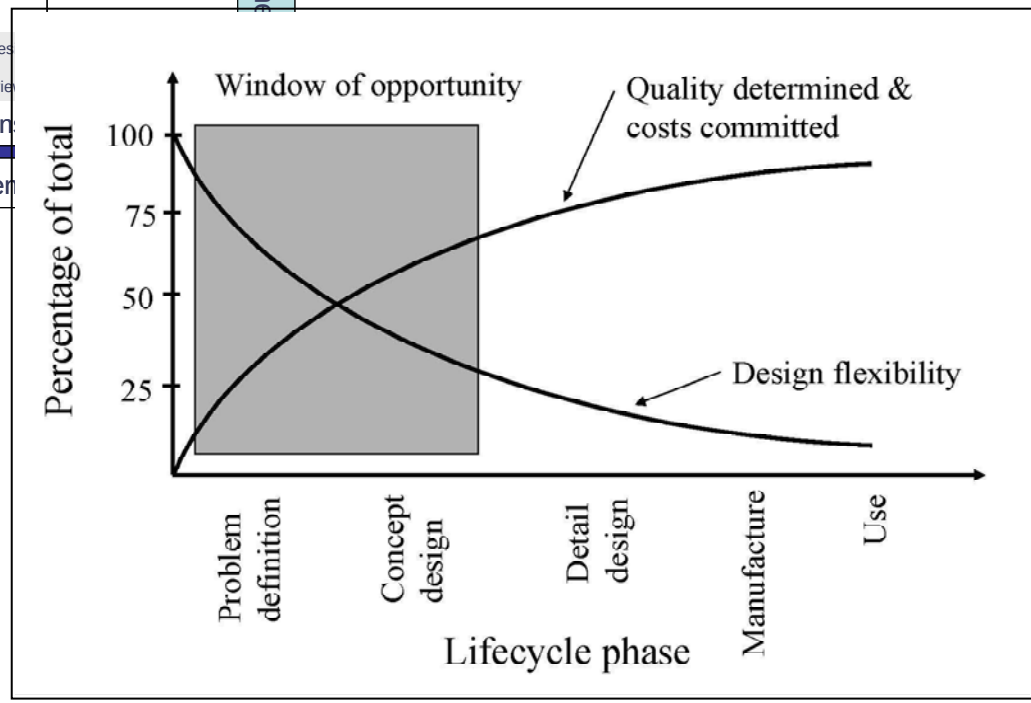


Figure adapted from Blanchard, S. & Fabrycky, W. J. (2006). *Systems Engineering and Analysis.* (4th ed.) Upper Saddle River, NJ: Prentice-Hall.

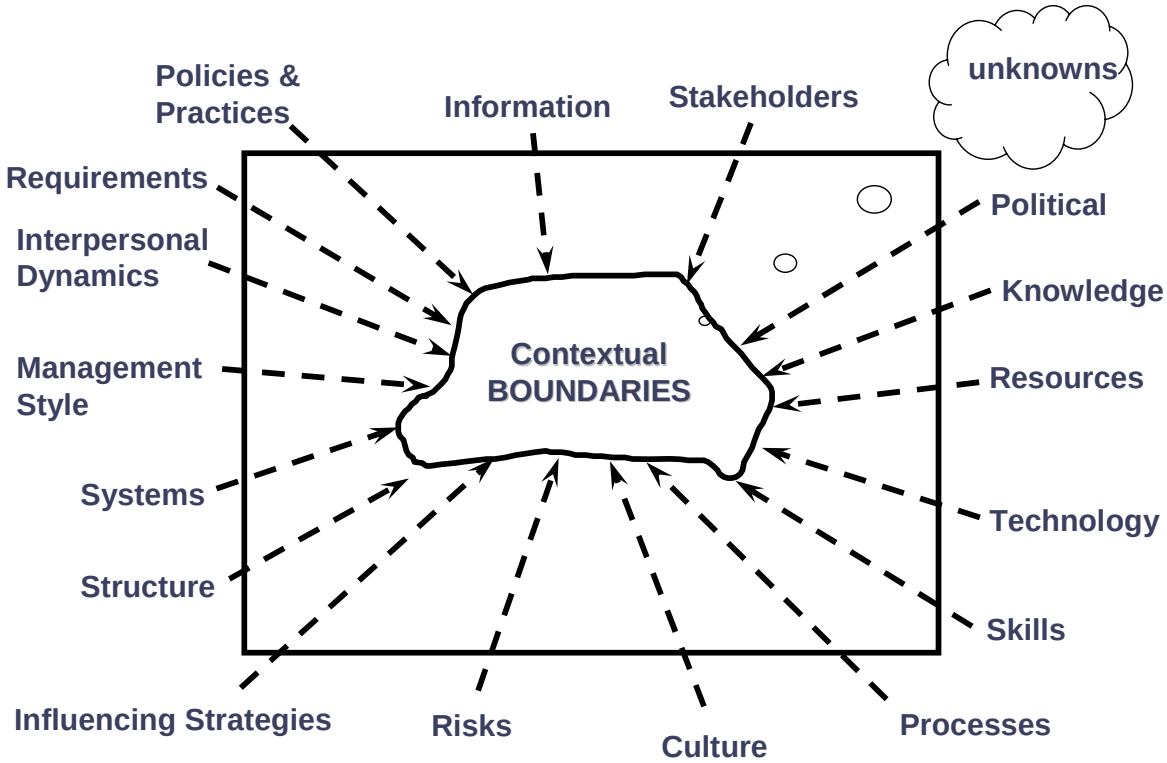
Get it right early!

- Importance of Conceptual Design
- Get testers involved (OT/DT/LFT)
- Understand mission environment
- Understand what constitutes operational effectiveness & suitability; what user really needs!
- Test early & often w/ honest assessment of risk to sustained mission capability



Source: Ford, R. B. & Barkan, P. (1995) "Beyond Parameter Design --A Methodology Addressing Product Robustness at the Concept Formation Stage", *Design for Manufacturability, 1995 Concurrent Engineering and Design Manufacturing Integration,* ASME DE-Vol. 81, J.R. Behun (Ed.), National Design Engineering Conference, Chicago, IL, March 13-16.

Program Context and Systems Evaluation

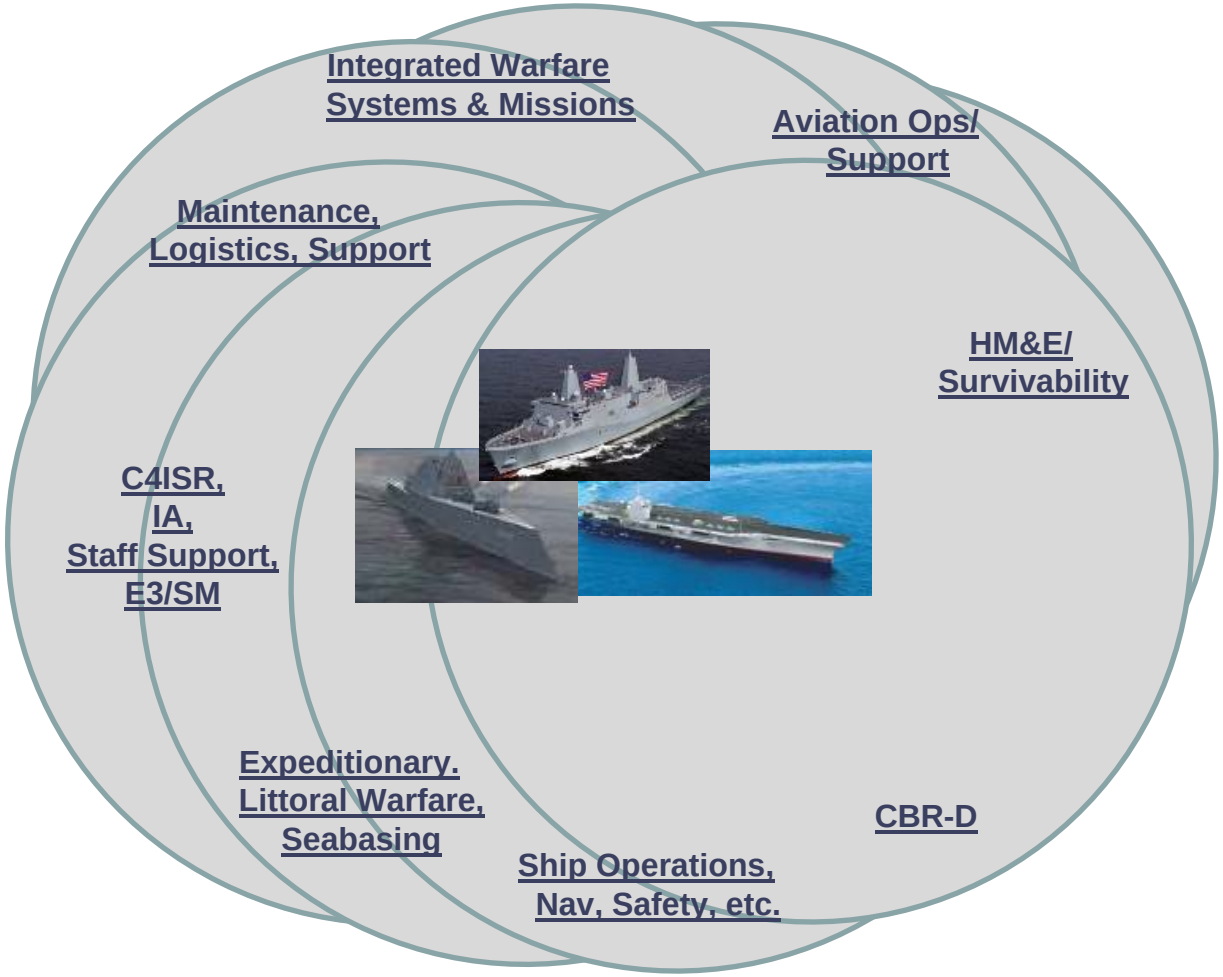


Implications for complex system T&E

- Understand mission environment and ensure testing explores those boundaries
- Evaluation of system/program performed in context of the program & many external and internal influences and drivers
- These also affect capabilities and limitations of T&E itself

Figure adapted from Blanchard, S. & Fabrycky, W. J. (2006*). Systems Engineering and Analysis.* (4th ed.) Upper Saddle River, NJ: Prentice-Hall.

Total Platform/System Mission Context



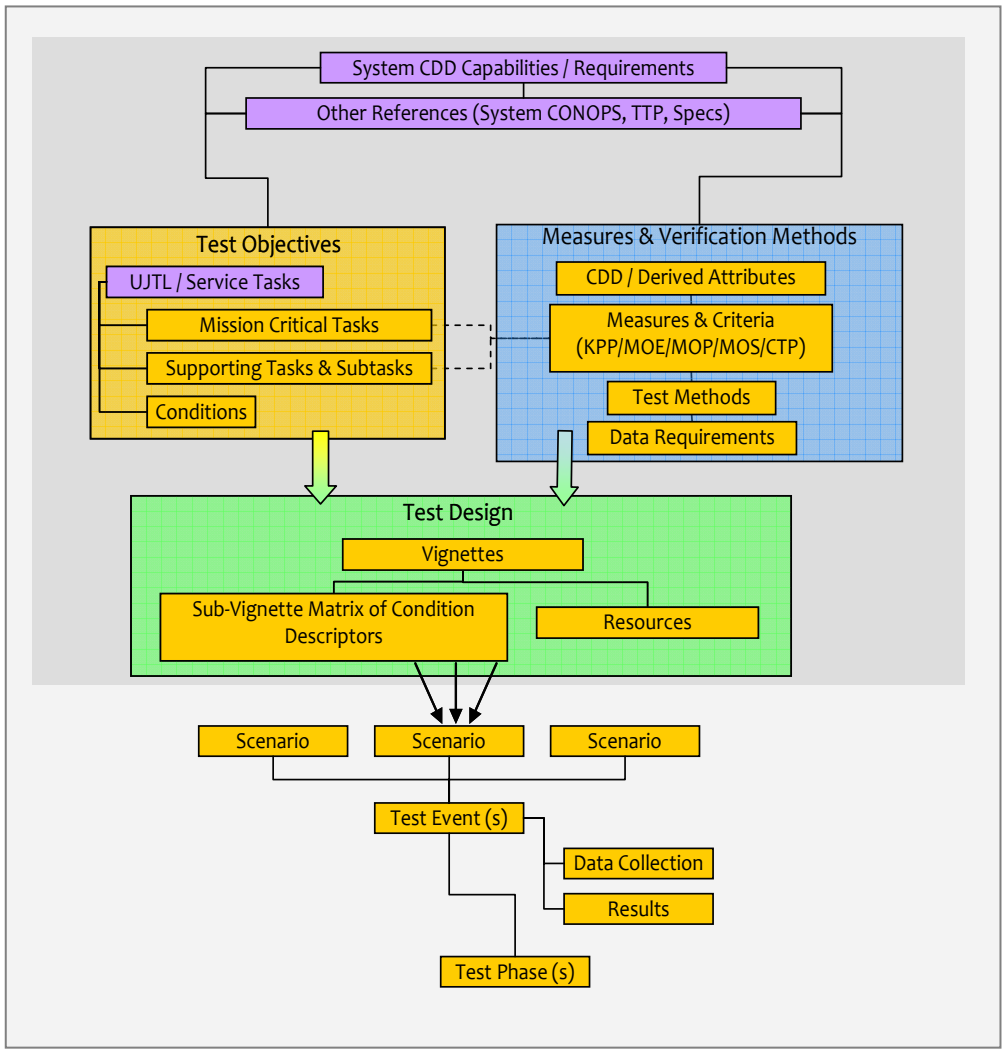
mplications for complex system T&E

•

ultiple, concurrent missions evaluated in complex scenarios

Mission Based Testing

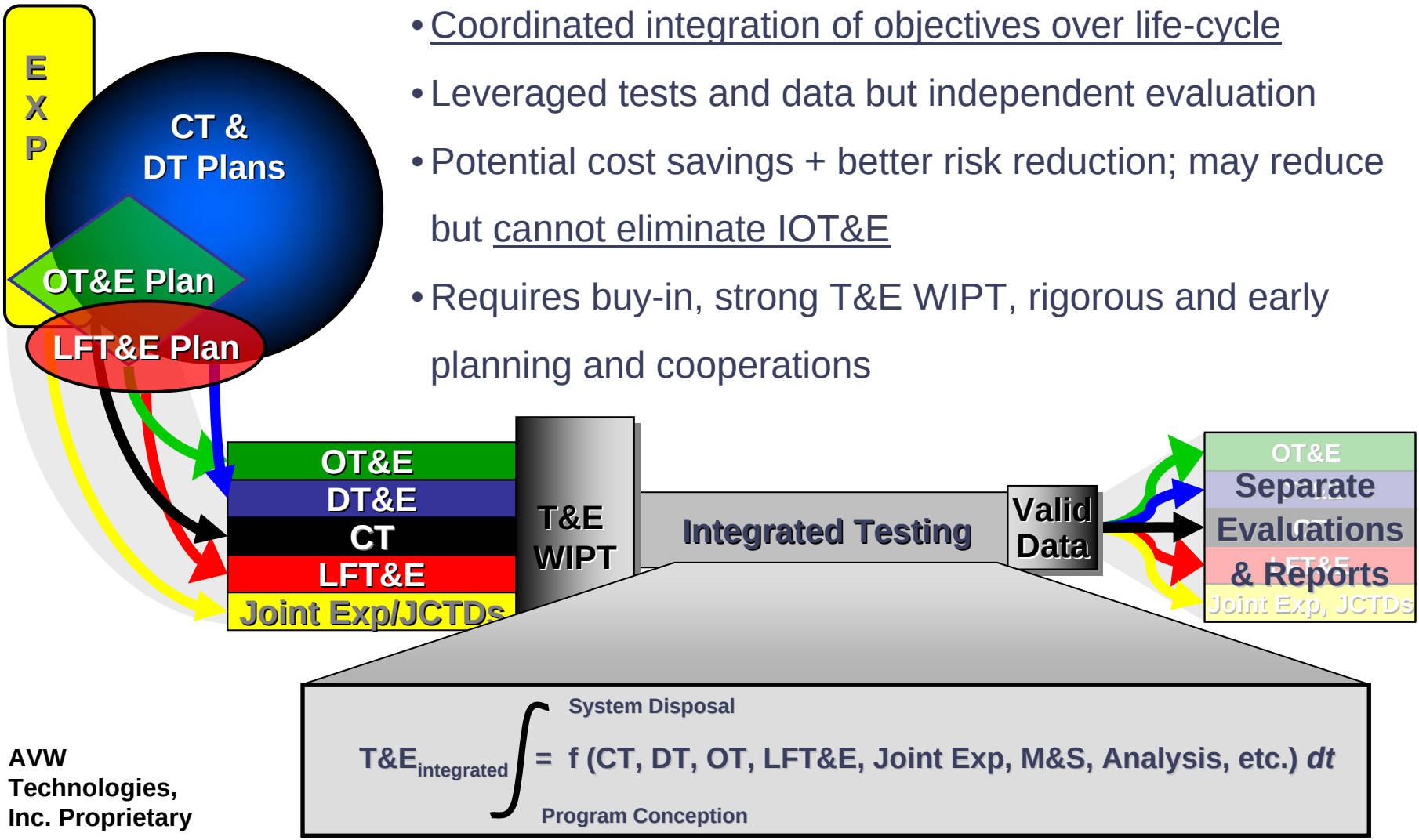
T&E Framework Toolset Architecture



- Describe discrete tasks to perform system missions in user's language
- Define conditions affecting task outcome
- Extract attributes & measures from requirements & other references; correlate to tasks
- Assign test methods & data requirements to measures
- Group tasks w/ conditions & measures into testable/meaningful vignettes
- Repeat vignettes to account for variability due to conditions and settings
- Test vignettes grouped into scenarios run during test events

Integrated Testing

- Planning and development of individual test objectives;
- Coordinated integration of objectives over life-cycle
- Leveraged tests and data but independent evaluation
- Potential cost savings + better risk reduction; may reduce but cannot eliminate IOT&E
- Requires buy-in, strong T&E WIPT, rigorous and early planning and cooperations



Integrated Testing

DT

- Test to specifications
- Limited test environment
- Focused on a specific set of criteria.
- Test threshold values not capability
- Critical technical parameters
- Integration testing designed around min performance criteria and interface specs.
- May not address all threats or missions.
- CT adds contractual issues

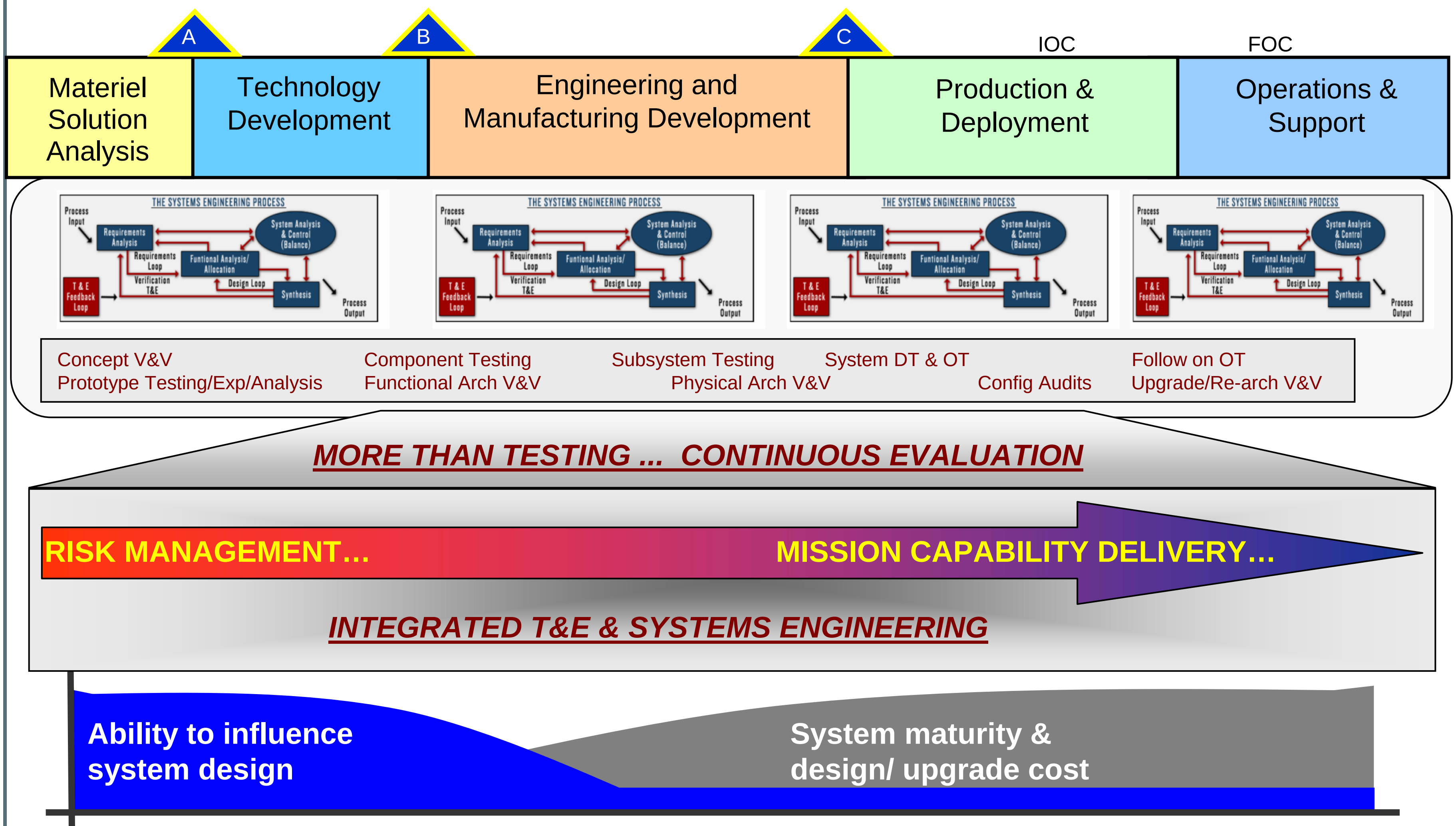
OT

- Operational environment & threat with end users & support
- End-to-end mission perf. & support
- Production representative; system/ family of systems
- Test overall capability of an item to meet user's mission needs and value added for mission accomplishment.
- Test the limitations and capabilities of an item so that:
- Employ and assess doctrine/TTP
- Independent IOT&E & LFT&E mandates (Title X)

THIS MUST TRANSFORM INTO A CONTINUUM OF TESTING

- **Increasing fidelity of technical and operational assessments**
- **Cooperating organizations**
- **Reduced budget and timeline ?**
- **Team/IPT structure not competitive**

Systems Engineering + T&E within the Acquisition Cycle



Design of Experiments
Process Overview

Project description and process decomposition

- Problem statement and objective of experiment (test)
- Response variables, and potential causal variables – Ishikawa fish bone.

Plan test matrix

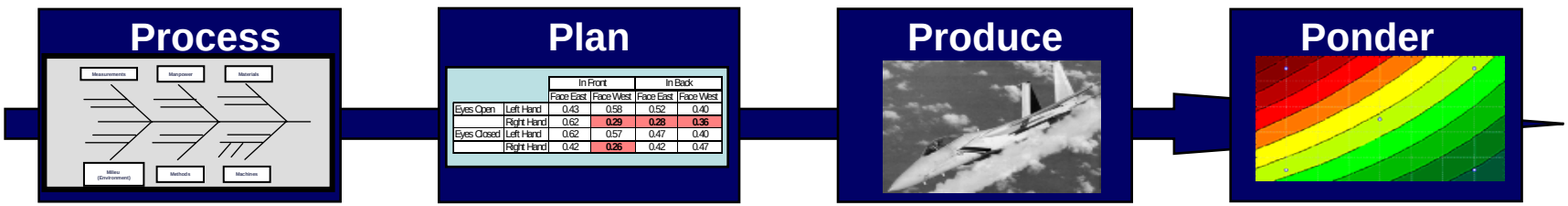
- Determine constraints, prioritize factors, and select statistical design (2^K vs. 3^K vs. mixed, Taguchi vs. classical arrays, full vs. fractional, non-linear effects?, replications?, blocking?)
- Write the test plan with sample matrices, profiles, and sample output; run sample analysis.

Produce observations

- Random run order & blocked against unknown effects
- Block runs to guard against uncontrollable unknown effects as needed.

Ponder the results

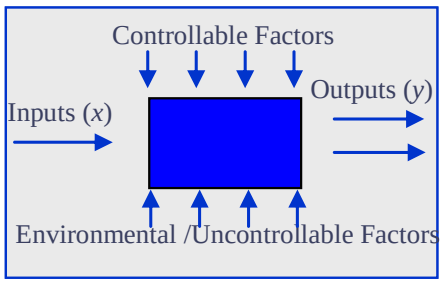
- Analyze and project data; draw conclusions, redesign test as necessary and assess results.
- Perform “salvo testing” (test-analyze-test); screen large # of factors then model

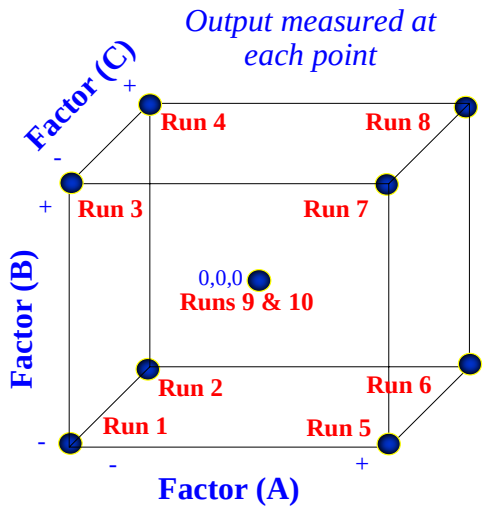


Design of Experiments
Test Matrix Development

- Partial or full matrix of varying settings for the factors (usually 2 or sometimes 3 level)
- Perform larger matrices in increments, eliminating factors that are shown to be non-factors through analysis
- Goal is to determine cause of variability in output based on input factors

Run	Setting	A	B	C
1	Factorial point	-1	-1	-1
2	Factorial point	-1	-1	+1
3	Factorial point	-1	+1	-1
4	Factorial point	-1	+1	+1
5	Factorial point	+1	-1	-1
6	Factorial point	+1	-1	+1
7	Factorial point	+1	+1	-1
8	Factorial point	+1	+1	+1
9	Center point 1	0	0	0
10	Center point 2	0	0	0

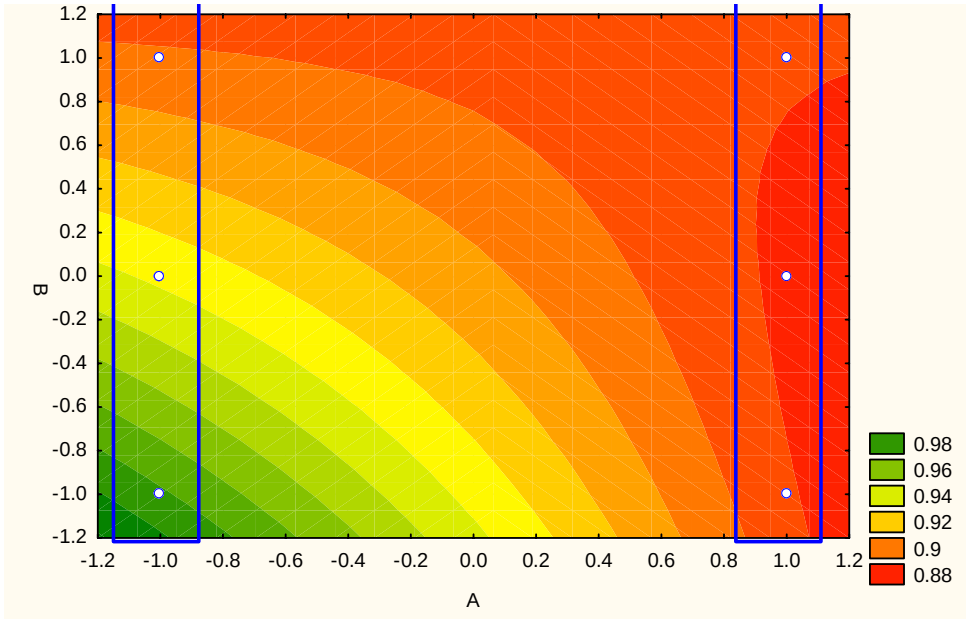




Adapted from USAF 53rd T&E Wing DOE Training Materials

Design of Experiments
Data Analysis

- Sample data analysis: produces regression model, predictions, response surface/curves as shown.
- Statistical analysis of the MOEs
- Exploration of mission performance variability across driving conditions



Tribble, J. E. (2008) "Applying Design of Experiments Methodology to Sortie Generation Rate T&E" *Proceedings of the 24th Annual NDIA Test & Evaluation Conference, February 25-28, 2008*. p. 20. Downloaded from: http://www.dtic.mil/ndia/2008test/agenda.pdf. Note: derived from actual test data using response surface analysis methods in Montgomery (2005), Schmidt & Launsby (2005).

Design of Experiments
Benefits

- Better way to design and test complex systems
- Systematically explores system performance, effectiveness, and suitability – breadth and depth of testing across the performance envelope
- Challenge assumptions and demonstrate real performance across the expected environment
- Better justification for sample sizes; potentially significant reduction from case or one factor at a time testing
- Better linkage between M&S and live test
- DOE works well in Mission Based Testing/Integrated Testing and relies on proper task derivation and attributes and conditions selection
- DOE can improve testing across all programs – it is simply smarter testing!

Conclusion

- Complex Systems
  - –Complex Systems– detail vs. dynamic complexity
  - –Holism
  - –Emergence

- Structuring T&E to Validate Complex Systems
  - –Understand program context and system mission context
  - –Test early, test often...
  - –Mission Based Test Design
  - –Integrated Testing
    - CT + DT + OT + LFT + ...
    - Integrated testing and data collection
    - But...Independent evaluation
    - T&E as part of SE life-cycle
    - Design of Experiments
- Questions