Undergraduate Curriculum Considerations for Systems Engineering (SE)

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March 30, 2012

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SE Context Overview

Systems Engineering - What is it?

SE Core Concepts

- Integrated Problem Solving
- Communications
- Process Control
- Systems Integration
- Value Integration

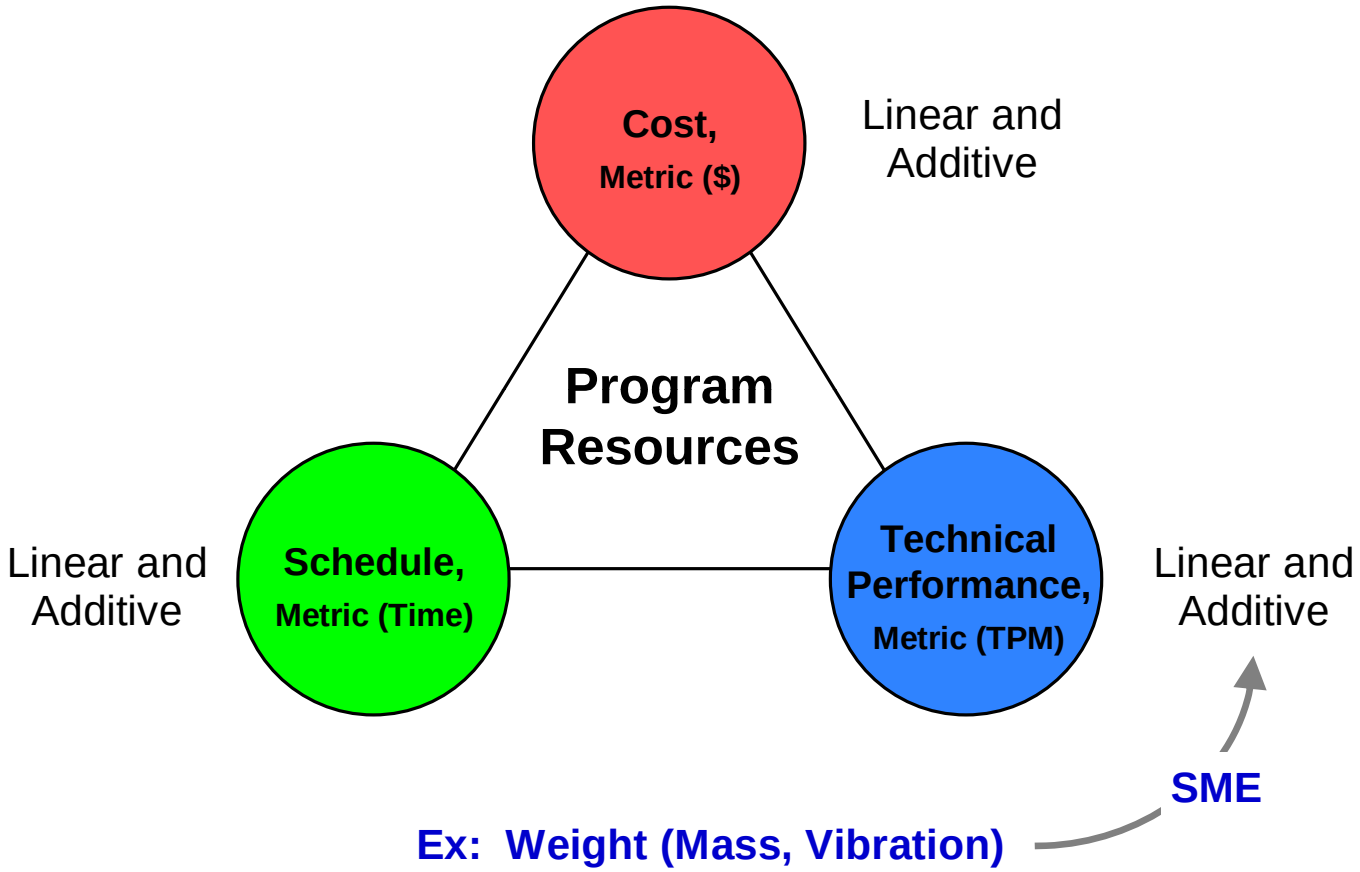
Summary / Conclusion

Systems Engineering - What is It?

The application of general systems theory to the industrial process

- Rests on a ***strong foundation of systems science and theory***.
- Applies to ***all types of industrial processes***: information management, facility configuration, product definition, and value management.
- Focuses on ***integrated problem solving***.

Systems Engineering Metrics



Subject Matter Experts (SMEs) – are used to convert ***nonlinear technical metrics*** to the required linear and additive metric for technical performance measure (TPM)

Ex. Environmental Engineering

Wastewater treatment 1950 to 1975 :

Consisted mostly of ***static structures*** – pipes and pumps

Surface water run off and control 1975 to present:

Consists of ***dynamic structures*** with sensors, gates, pumps and ***predictive modeling***

Surface water run off & control, current to future:

Is now being addressed by ***distributed control structures*** designed using ***distributed models*** of rain events

Ex. Environmental Engineering

Environmental design solutions

Have moved from ***static structures and point solutions*** to ***dynamic distributed structures*** that include sensors, predictive modeling, and adaptive system configurations

Traditional civil engineering domain tasks

Are being integrated with more ***system dynamic analysis and modeling approaches***

These integrated approaches create more value, and achieve the same environmental goals.

Ex. Electrification of Transportation

Transitioning transportation to electric power is another major distributed systems problem area.

A national initiative requires conversion from oil-based fuel to electricity.

This presents a ***large scale, socio-technical problem*** that has:

- ***Existing components*** - roads, electric distribution systems
- ***New components*** - electric vehicles, charging station
- ***New design challenges***

Demand for SE Capabilities

Systems engineers must have the skills to analyze, evaluate and communicate:

- ***System functions***
- ***Requirements***
- ***Alternative solutions***

associated with these types of large scale projects

Phased design and development of loosely coupled distributed systems is at the heart of the practice of systems engineering.

Undergraduate study in systems engineering must prepare students to ***effectively integrate with specialty engineering experts and executive management*** to facilitate system solutions.

SE Core Concepts

Systems engineering concepts are distinct from other specialty engineering disciplines since they focus on integrated problem solving.

These concepts include:

- **Communication**
- **Process Control (life cycle processes, team building, management skills)**
- **Systems Integration**
- **Value Integration**

SE Core Concept

Integrated Problem Solving

Integrated Problem Solving

Well-defined problem space:

Clearly states the ***inputs, outputs and associated problem assumptions*** (e.g., civil engineering - road design; electrical engineering - circuit design; software engineering - object design)

Closed solution space:

Has a ***well-defined, unique solution***

A simple problem:

Has a ***small number of variables, solution steps*** and ***acceptable solutions***

A complex problem:

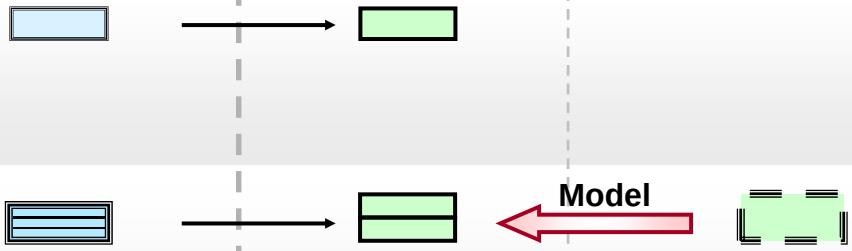
Contains ***one or more simple problems*** with ***a large number of variables, solution steps*** and ***acceptable solutions***.

Problem-Solving Knowledge & Skills

Systems Analysis	*Problem Type*	*Mathematical Modeling*
Structured, disciplined concepts	**Well-defined problems, closed solutions**	Domain & disciplinary knowledge
Structured, disciplined concepts Analytical tools, including specifications	**Ill-defined problems, closed solutions**	Domain & disciplinary knowledge Linear programming; micro economics
Structured, disciplined concepts Analytical tools, including specifications Systems engineering and systems approach	**Ill-defined problems, open-ended solutions**	Domain & disciplinary knowledge Linear programming; micro economics Multi-objective decision making Risk analysis and management
Structured, disciplined concepts Analytical tools, including specifications Systems engineering and systems approach Extensive systems engineering	**Complex ill-defined problems, open-ended solutions**	Domain & disciplinary knowledge Linear programming; micro economics Multi-objective decision making Risk analysis and management Stochastic methods Control theory

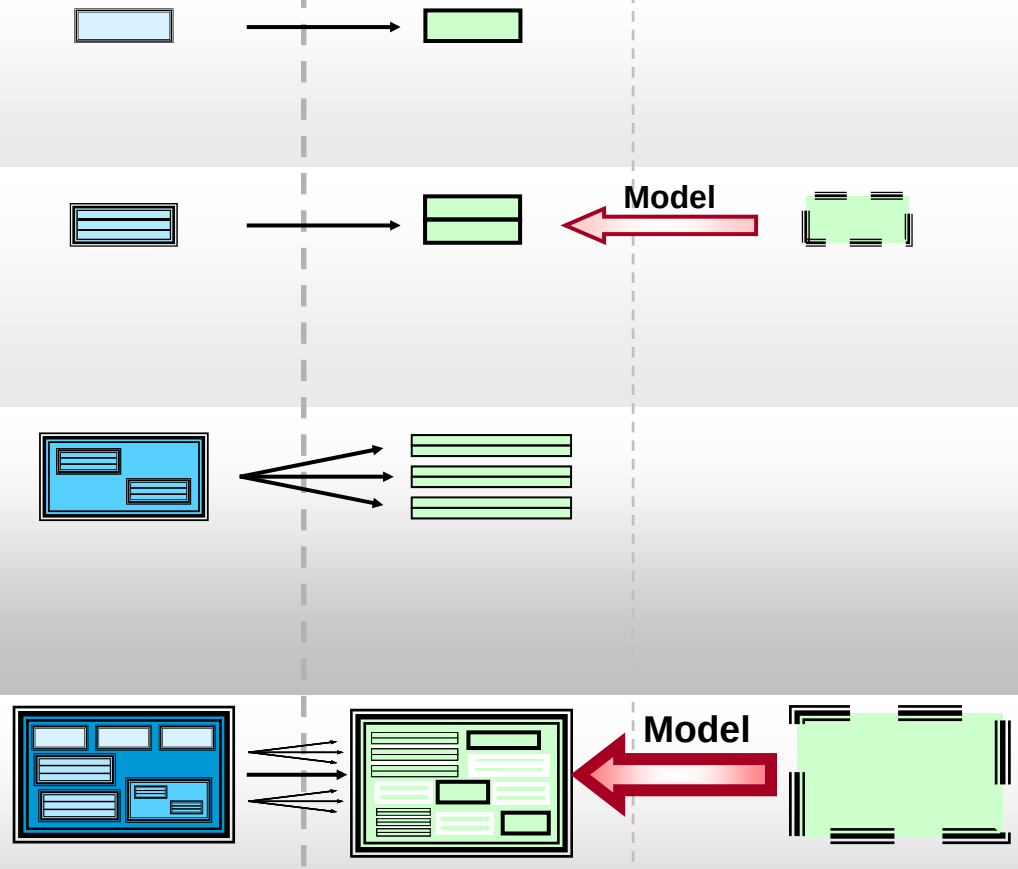
Adapted from Figure 9.1 in *Introduction to the Engineering of Complex Systems*, Brian Mar

Problem-Solution Types

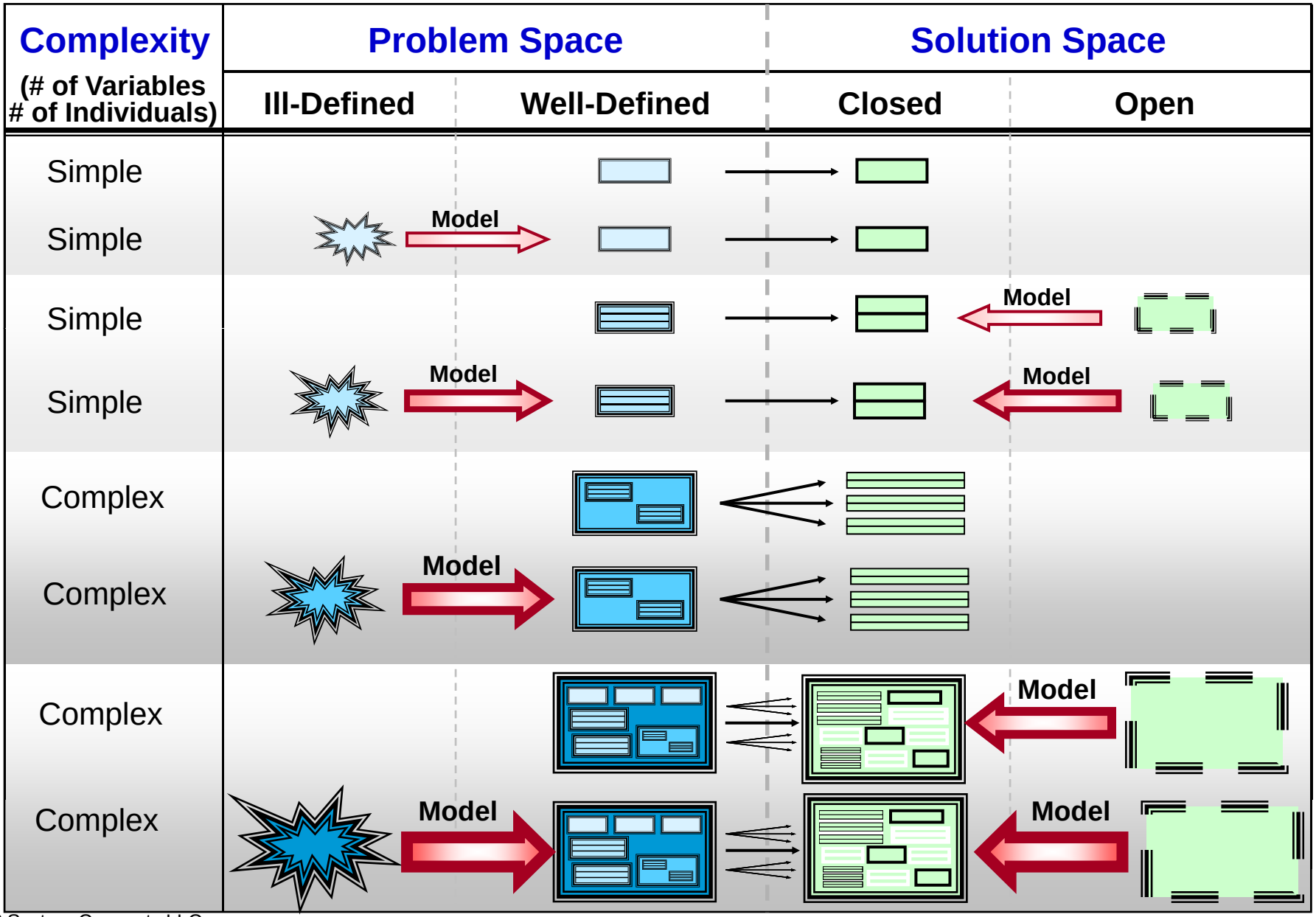
Complexity (# of Variables # of Individuals)	Problem Space	Solution Space
	Well-Defined	Closed
Simple	**Simple, Well-Defined Problem with Closed Solution Space**	
Simple		

Problem-Solution Types

Complexity (# of Variables # of Individuals)	Problem Space	Solution Space
	Well-Defined	Closed
Simple	**Simple, Well-Defined Problem with Closed Solution Space**	
Simple		Model
Complex	**Complex, Well-Defined Problem Set with Closed Solution Space**	
Complex		Model



Problem-Solution Types



SE Core Concept

Communications

Communication Knowledge & Skills

Writing, speaking, computing and information literacy:

Integrated text processing system and web based information production and retrieval

Database design; information schema development:

Standard SQL, NoSQL and big-data concepts

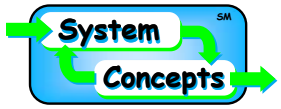
Model- and simulation-based design capture:

Model system context, concept and solution sets

Optimizing design-capture process and environments:

Selection of best set of tools and processes for the current design task

Communication Knowledge & Skills



Communication Tools	*Learned Capabilities*	*Communication Skills*
Word processing environments; networked information systems	**Computing and information literacy**	Basic technical communications
Word processing environments; networked information systems Database design capture environments	**Database design capture**	Basic technical communications Written and graphical design capture; natural language processing
Word processing environments; networked information systems Database design capture environments Shared vision/object based simulation environments	**Model- and simulation-based design capture**	Basic technical communications Written and graphical design capture; natural language processing Text, graph, and formal language representations; Abstract relation types Automatic generation of specification and solutions
Word processing environments; networked information systems Database design capture environments Shared vision/object based simulation environments Optimizing specification and design environments	**Optimizing design capture process and environments**	Basic technical communications Written and graphical design capture; natural language processing Text, graph, and formal language representations; Abstract relation types Automatic generation of specification and solutions Real time problem definition and solution analysis

Adapted from Figure 10.1 in *Introduction to the Engineering of Complex Systems*, Brian Mar

SE Core Concept

Process Control - Life Cycle Processes

Systems Engineering Processes

LIFE CYCLE 'PHASES' | **Initialization** | **Implementation** | **Operations**

Typical High-Tech Commercial Systems Integrator

Study Period				Implementation Period			Operations Period		
User Reqts Definition Phase	Concept Definition Phase	System Specification Phase	Acq. Prep. Phase	Source Select. Phase	Development Phase	Verification Phase	Deployment Phase	Operations & Maintenance Phase	Deactivation Phase

Typical High-Tech Commercial Manufacturer

Study Period			Implementation Period			Operations Period		
Product Requirements Phase	Product Definition Phase	Product Development Phase	Engr. Model Phase	Internal Test Phase	External Test Phase	Full-Scale Production Phase	Manufacturing, Sales & Support Phase	Deactivation Phase

ISO/IEC 15288

Concept State	Development Stage	Production Stage	Utilization Stage / Support Stage	Retirement Phase

US Department of Defense (DoD) 5000.2

A	B	C	IOC	FOC
Pre-systems Acquisition: Concept and Technology Development	Systems Acquisition: System Development & Demonstration	Systems Acquisition: Production & Deployment		Sustainment: Operations & Support (including Disposal)

US Department of Energy (DOE)

Project Planning Period			Project Execution			Mission	
Pre-Project	Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Acceptance	Operations

Typical Decision Gates: New Initiative Approval | Concept Approval | Development Approval | Production Approval | Operational Approval | Deactivation Approval

Adapted from INCOSE SE Handbook v. 3

SE Core Concept

Process Control - Team Building

Team Building Knowledge & Skills

Building Small Teams:

Informal teams of 3 to 12 individuals

Leadership and Formal Team Building:

Establish a leadership role with formal distributed teams

Creating Hierarchies of Product Teams:

Mapping team membership to product and processes

Managing Complex Team Structures:

Adapting organizational goals, objectives and processes to distributed teams working in a concurrent collaborative manner.

Team Building Knowledge & Skills

Team Building Tools	*Team Processes*	*Team Work Concepts*
Developing Shared Visions	**Building Small Teams**	Disciplined work habits
Developing Shared Visions Team Architecture; group consensus building	**Leadership and Formal Team Building**	Disciplined work habits Leadership and empowerment basics
Developing Shared Visions Team Architecture; group consensus building Formal engineering environments and design capture tools	**Creating Hierarchies of Product Teams**	Disciplined work habits Leadership and empowerment basics Group decision-making processes; risk analysis and management Politics, cultures, and rice bowls
Developing Shared Visions Team Architecture; group consensus building Formal engineering environments and design capture tools Team building in real world situations	**Managing Complex Team Structures**	Disciplined work habits Leadership and empowerment basics Group decision-making processes; risk analysis and management Politics, cultures, and rice bowls

Adapted from Figure 12.1 in *Introduction to the Engineering of Complex Systems*, Brian Mar

SE Core Concept

Process Control - Management Processes

Management Process Knowledge & Skills

Personal time management:

Building a valued personal brand, dependable

Formal scheduling & resource allocation:

N Squared Charts, Design Structure Matrices, Gantt Charts, Critical Path Network

Planning, tasking, controlling complex tasks:

Design Structure Matrix and Critical Path Network Optimization

Managing life cycle implementation risks:

Integrated risk management approach across multiple system levels and value sets

Management Process Knowledge & Skills

Problem Definition Processes	*Management Development Processes*	*Problem Solving Processes*
Structured and disciplined planning concepts	**Personal time management**	Disciplined work habits
Structured and disciplined planning concepts Critical path & other scheduling algorithms; basic life cycle models	**Formal scheduling & resource allocation**	Disciplined work habits Linear programming and micro economics
Structured and disciplined planning concepts Critical path & other scheduling algorithms; basic life cycle models Systems engineering and program management plans and implementation	**Planning, tasking, controlling complex tasks**	Disciplined work habits Linear programming and micro economics Work breakdown and tasking; risk analysis and management Control and capability processes
Structured and disciplined planning concepts Critical path & other scheduling algorithms; basic life cycle models Systems engineering and program management plans and implementation Engineering of complex systems with systems engineering processes	**Managing life cycle implementation risks**	Disciplined work habits Linear programming and micro economics Work breakdown and tasking; risk analysis and management Control and capability processes

Adapted from Figure 13.1 in *Introduction to the Engineering of Complex Systems*, Brian Mar

SE Core Concept

Systems Integration

Systems Integration

Mission Function Identification and Control:

Customer primary function (what must be accomplished by the integrated system)

System Function Synthesis and Evaluation :

Function provided by the candidate system, alternative system functional configurations are identified and evaluated.

System Architecture Integration and Evaluation:

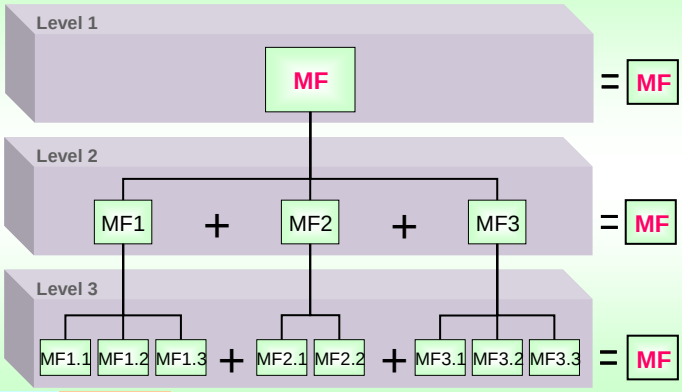
Integrated system architecture alternatives are identified and evaluated.

Integration Metrics:

Specific systems are evaluated for operational effectiveness, operational suitability, life-cycle cost and risk.

Systems Integration

Mission Function

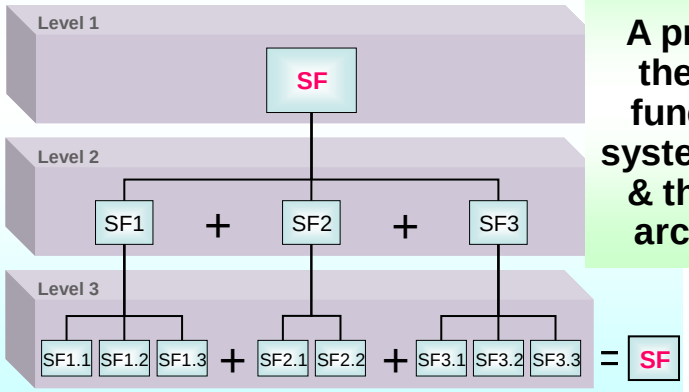


A property of the system function that determines how well the mission function is performed

Operational Effectiveness

Risk

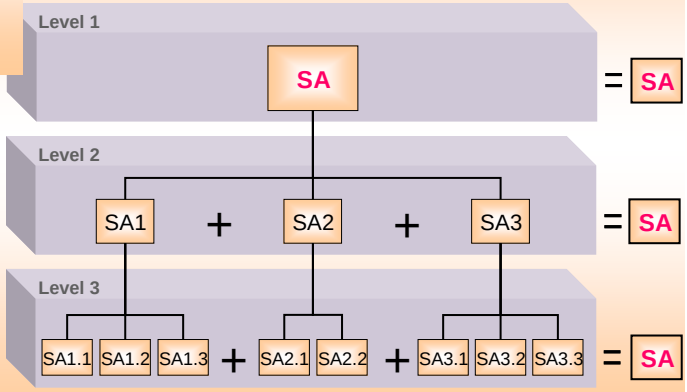
A property of the mission function, the system function & the system architecture



System Function

Operational Suitability **Life Cycle Cost**

Properties of the system architecture



System Architecture

Adapted from Figure 16 in "Foundational Systems Engineering (SE) Patterns for a SE Pattern Language," 2006 INCOSE IS, J. Simpson and M. Simpson

SE Core Concept

Value Integration

Value Integration

Select Key Mission Value Metrics:

Often cost per unit of system function ($/sf)

Identify System Performance Metrics:

Metrics that clearly state how well a system must function
Measured as a linear function of dollars and time

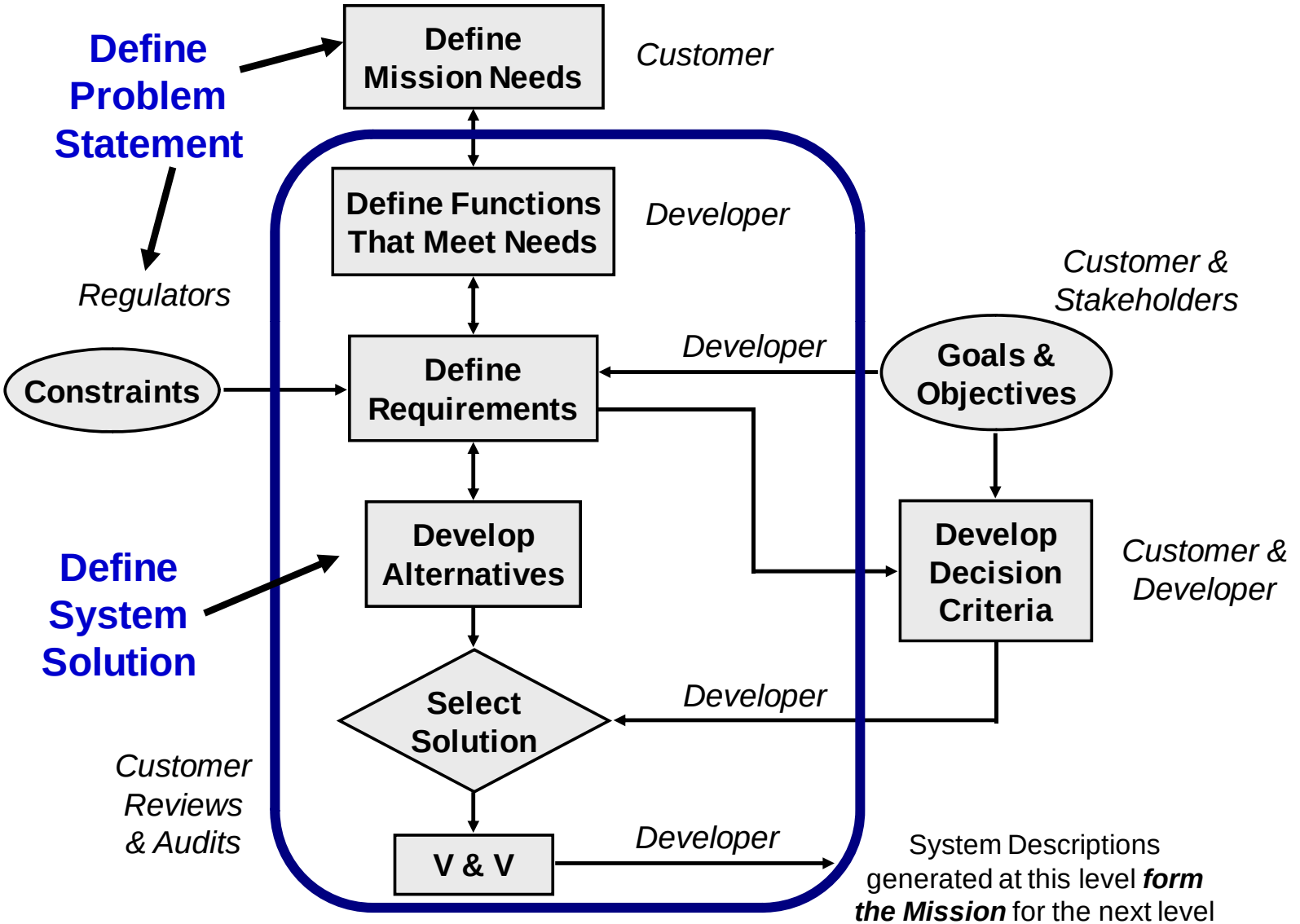
Select Decision Makers and Decision Process:

Identify decision makers, decision values and decision process

Perform Trade Study:

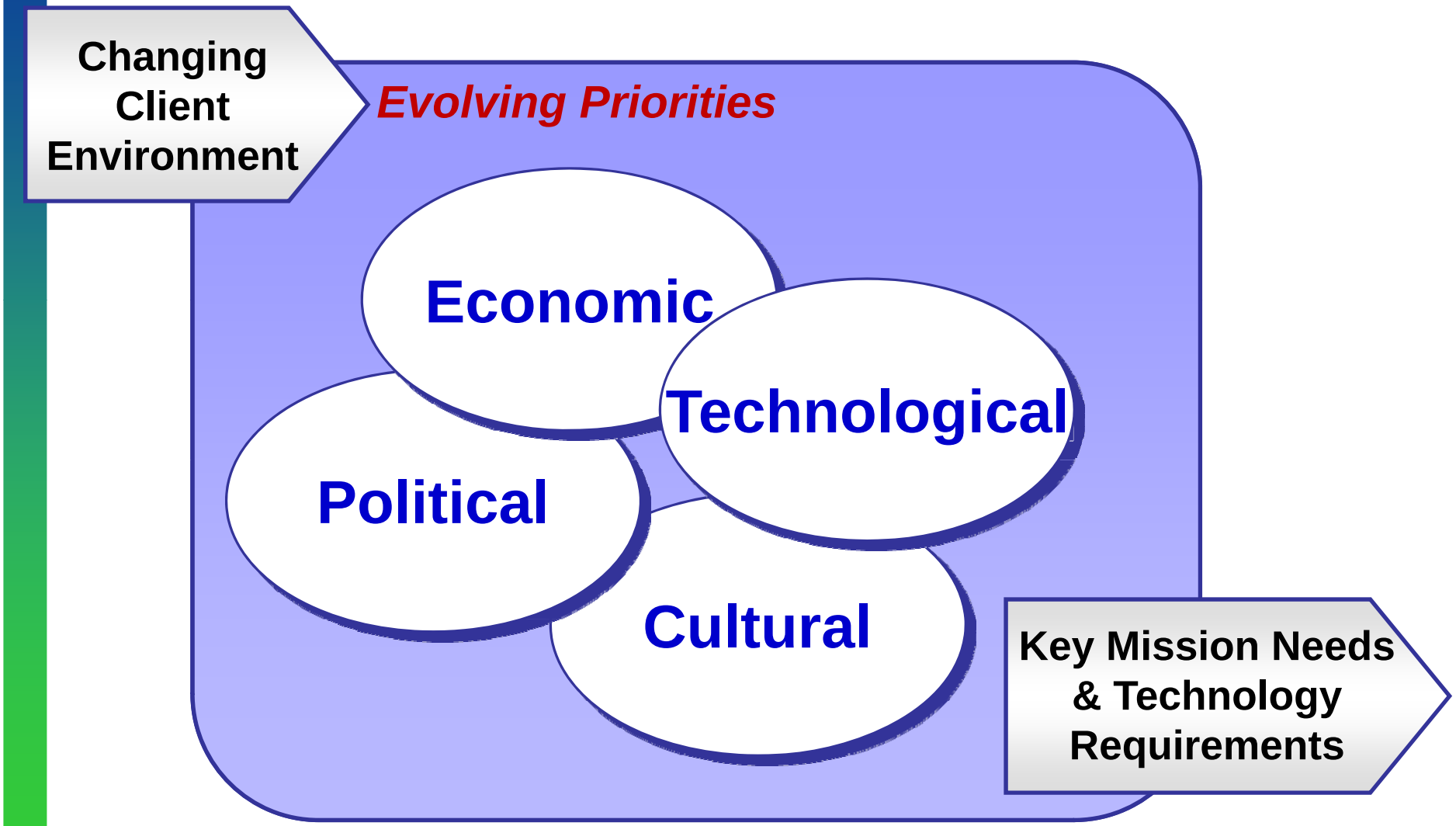
Structured process used to select the best system alternative

Value Integration



Adapted from "FRAT – A Basic Framework for Systems Engineering," INCOSE 2002 IS, Mar & Morais

Value Integration of Client's Needs



Key Considerations

For a Changing Problem Space or System Environment

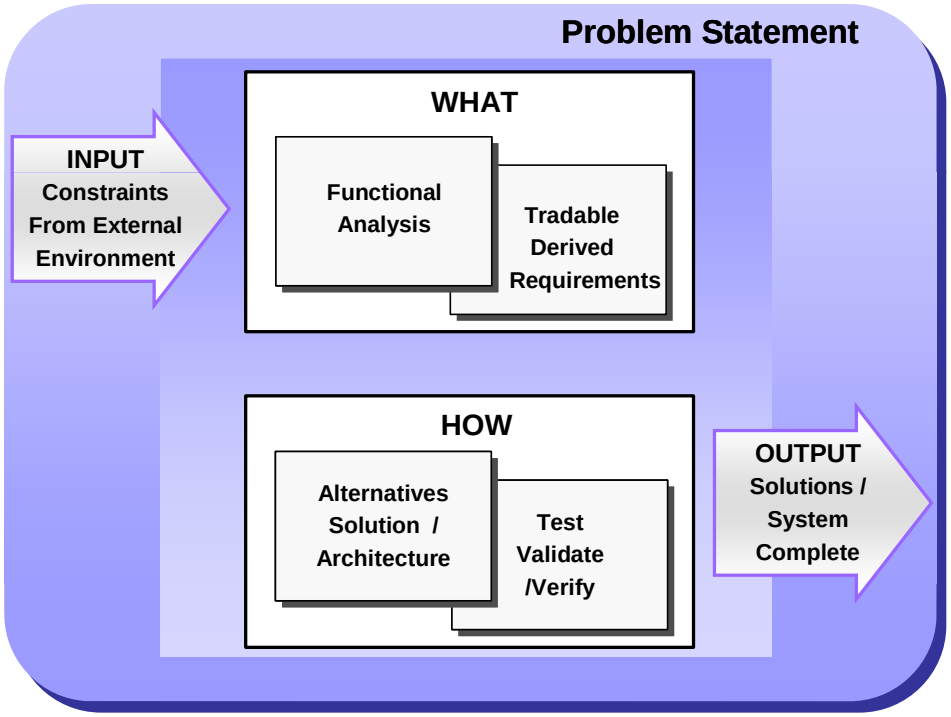
1. ***Political***
   - Regulatory Infrastructure
   - Legal Infrastructure
   - Political Infrastructure
2. ***Economic***
   - Economic Structure of Customers
   - Distribution of Resources
3. ***Technological***
   - Existing Base
   - Operational Practices
   - State of Technology
4. ***Cultural***
   - Public consciousness
   - Demographic features
   - Views/biases of power brokers

1. ***Are all four kinds of client needs addressed?***
2. ***Are these needs prioritized (between each other) by the client? by provider?***
3. ***Are there specific organizational components already assigned to incorporate these needs?***
4. ***Since each aspect requires a different kind of client/provider interface, is there infrastructure to handle?***
5. ***How are the interfaces between the political, economic, technological and cultural values/aspects handled internal to unit? to enterprise?***

Summary / Conclusions

The systems engineering approach is based on:

- ***Define*** problems before seeking solutions
- ***Search*** for solutions that examines tradeoffs between alternative solution sets
- ***Utilize*** traceable integration process that verifies that the product meets requirements and performs needed functions
- ***Deploy*** information management system that can provide each team member **and the customer** with any information concerning the system that has been generated.



Adapted from "Back to Basics," INCOSE 1992 Symposium, Brian Mar

- **Questions?**
- **Comments?**

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